NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

AUTOMATION AND EXTENSION OF
LDV MEASUREMENTS OF OFF-DESIGN FLOW
IN A SUBSONIC CASCADE WIND TUNNEL

by

Kenneth Douglas Murray

June 1989

Thesis Advisor: Raymond P. Shreeve

Unclassified

Security Classification of this page

REPORT DOCUMENTATION PAGE

1a Report Security Classification Unclassified	1b Restrictive Markings
2a Security Classification Authority	3 Distribution Availability of Report
2b Declassification/Downgrading Schedule	Approved for public release; distribution is unlimited.
4 Performing Organization Report Number(s)	5 Monitoring Organization Report Number(s)
6a Name of Performing Organization: Naval Postgraduate School — 6b Office Symbol: 31	7a Name of Monitoring Organization: Naval Postgraduate School
6c Address *(city, state, and ZIP code)*: Monterey, CA 93943-5000	7b Address *(city, state, and ZIP code)*: Monterey, CA 93943-5000
8a Name of Funding/Sponsoring Organization — 8b Office Symbol	9 Procurement Instrument Identification Number
8c Address *(city, state, and ZIP code)*	10 Source of Funding Numbers: Program Element Number — Project No — Task No — Work Unit Accession No

11 Title AUTOMATION AND EXTENSION OF LDV MEASUREMENTS OF OFF-DESIGN FLOW IN A CASADE WIND TUNNEL

12 Personal Author(s) Kenneth Douglas Murray

13a Type of Report	13b Time Covered	14 Date of Report *(year, month,day)*	15 Page Count
Engineer'sThesis	From To	June 1989	147

16 Supplementary Notation The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

17 Cosati Codes			18 Subject Terms *(continue on reverse if necessary and identify by block number)*
Field	Group	Subgroup	Laser-Doppler Velocimetry, LDV, Cascade Wind Tunnel, Controlled Diffusion Blades, Off-design Cascade Flow, Viscous Cascade Flow

19 Abstract *(continue on reverse if necessary and identify by block number*

A two-component laser-Doppler velocimetry system was successfully automated to speed the data acquisition and reduction process for flow measurements in a subsonic linear cascade wind tunnel. A three-axis traverse table was installed for computer controlled positioning of the LDV probe volume and a modification was made to permit measurements close to test blade surfaces. Commercial software was used for control and acquisition of the LDV data. Software was generated in-house to record tunnel conditions and to reduce and present the survey data. Detailed measurements were made of the flow through a controlled diffusion compressor cascade at an inlet flow angle of 48 degrees (8 degrees above design) to extend a database for viscous code validation. Test conditions were held nominally at $M = 0.25$ and $Re_C = 720000$. The flow was shown to remain attached at the blade trailing edge but the measurements also indicated the presence of a less stable flow field in the blade passage when compared with previous observations at lower inlet flow angles.

Keywords: theses, fighter aircraft, [illegible] fighting, turbomachinery, high angle of attack, [illegible] (KR)

20 Distribution/Availability of Abstract	21 Abstract Security Classification
[X] unclassified/unlimited [ ] same as report [ ] DTIC users	Unclassified

22a Name of Responsible Individual	22b Telephone *(Include Area code)*	22c Office Symbol
Raymond P. Shreeve	(408) 646-2593	67Sf

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted — security classification of this page

All other editions are obsolete — Unclassified

Approved for public release; distribution is unlimited.

Automation and Extension of LDV Measurements of Off-design Flow in a Cascade Wind Tunnel

by

Kenneth Douglas Murray
Lieutenant, United States Navy
B.S., United States Naval Academy, 1982
M.S., Naval Postgraduate School, 1989

Submitted in partial fulfillment of the requirements for the degree of

ENGINEER IN AERONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
June 1989

Author: Kenneth D Murray
Kenneth Douglas Murray

Approved by: Raymond P Shreeve
Raymond P.Shreeve, Thesis Advisor

Sheshagiri. K. Hebbar, Second Reader

E.R. Wood
E. Roberts Wood, Chairman, Department of Aeronautics and Astronautics

G.E. Schacher
Gordon E. Schacher, Dean of Science and Engineering

ABSTRACT

A two-component laser-Doppler velocimetry system was successfully automated to speed the data acquisition and reduction process for flow measurements in a subsonic linear cascade wind tunnel. A three-axis traverse table was installed for computer controlled positioning of the LDV probe volume and a modification was made to permit measurements close to test blade surfaces. Commercial software was used for control and acquisition of the LDV data. Software was generated in-house to record tunnel conditions and to reduce and present the survey data. Detailed measurements were made of the flow through a controlled diffusion compressor cascade at an inlet flow angle of 48 degrees (8 degrees above design) to extend a database for viscous code validation. Test conditions were held nominally at $M = 0.25$ and $Re_C = 720000$. The flow was shown to remain attached at the blade trailing edge but the measurements also indicated the presence of a less stable flow field in the blade passage when compared with previous observations at lower inlet flow angles.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

SYMBOLS:

c	blade chord
C_{p12}	reference velocity normalizing loss coefficient
d_f	fringe spacing
K,κ	LDV beam half angle
L	focal length
M	Mach number
P	total pressure
p	static pressure
R_e	Reynolds number
T	temperature
u	velocity component in the X direction
u'	velocity component parallel to the blade surface
V	velocity
v	velocity component in the Y direction
v'	velocity component normal to the blade surface
V_{ref}	inlet reference velocity
w	local passage width
X'	horizontal distance, LDV coordinate system
X, x	horizontal distance, tunnel coordinate system
X_V	non-dimensional velocity
Y'	spanwise distance, LDV coordinate system

Y, y	vertical distance, tunnel coordinate system
Z'	vertical distance, LDV coordinate system
Z	spanwise distance, tunnel coordinate system

GREEK LETTERS:

β	air flow angle
ε	turbulence intensity (%)
ϕ	roll angle
γ	ratio of specific heats; or yaw angle
η	blade geometry: distance normal to the chordwise direction
λ	wavelength
ρ	density
σ	blade solidity; or standard deviation
ϖ	mass averaged total pressure loss coefficient
ξ	blade geometry: distance in the chordwise direction

SUBSCRIPTS/SUPERSCRIPTS:

1	station upstream of the test blade
2	station downstream of the test blade
atm	atmospheric condition
c	blade chord
loc	local condition
m	LDV measured velocity component
p	plenum condition
ref	inlet reference condition

ACKNOWLEDGMENTS

The reported work was carried out in support of the Naval Air Systems Command's Air Breathing Propulsion Research Program under Mr. George Derderian (AIR 931E) and funded for equipment through the Naval Postgraduate School block-funded research program. I would also like to especially thank Dr. R. P. Shreeve, Director of the Turbopropulsion Laboratory, for his instruction and guidance in preparing me for the work done in this thesis.

I. INTRODUCTION

A. HISTORICAL BACKGROUND

U.S. Navy interests in the development of agile fighter aircraft have prompted studies into high angle-of-attack aerodynamics and the associated studies of stall phenomena in turbomachinery. Future engines will need to be more tolerant of off-design flow conditions, especially the compressor sections where inlet distortion will be prevalent at high angle-of-attack conditions. Similar characteristics are required of VSTOL and STOVL engines, which face distortion from exhaust re-ingestion during operation near the ground. Consequently, compressors for the future will require new techniques in blade design to prevent blade stall over the expanded flight envelope.

1. Compressor Design

Until quite recently, the design of axial-flow compressors has been based on empirical data such as are presented in NASA SP-36[Ref. 1]. Traditional design methods have relied on two-dimensional cascade flow models for generating the blade geometries and full-scale three-dimensional testing for validating stage performance. The empirical design approach works adequately for on-design flow conditions, however, the present development procedure also becomes very expensive for a typical multi-stage compressor, usually requiring many test builds before the design is proven to have satisfactory on- and off-design performance suitable for production.

2. Controlled Diffusion Blades

Developments in computer processing power and advances in computational fluid dynamics (CFD) have advanced the design process for axial flow compressors. One development which addresses the design of blade geometry is the concept of controlled diffusion blades.

Using computer modeling techniques, the blade shape is manipulated until an optimized pressure profile is obtained. The pressure profile is chosen such that the adverse pressure gradient along the suction surface does not lead to separation before the trailing edge, and shock formation is minimized in the transonic regime. The resulting blade geometry is significantly different from traditional blade shapes which were usually selected from families of shapes defined by the camber line and distribution of thickness. In Figure 1 the profiles of a double circular arc (DCA) blade and a controlled diffusion (CD) blade, which was designed to replace it, are compared. The blade geometry was obtained from work conducted at NASA Lewis Research Center by Sanger in 1982 [Ref. 2].

Losses across the reference DCA blade row were measured by Himes in the U.S. Naval Postgraduate School Subsonic Cascade Wind Tunnel using pressure probe survey techniques [Ref. 3]. A follow-on study was conducted by Koyuncu to measure the losses across the CD blade row [Ref. 4]. Figure 2 shows the loss profile comparison for the DCA and CD blades. The CD blades were found to have less losses at design conditions (inlet flow angle equal to 38.91 degrees) when compared to the DCA blades. At higher incidence angles, based on limited data, the CD blades tend to have comparable losses. A comparison of the experimental results with computer code design predictions was presented by Sanger and Shreeve [Ref. 5]. Surface pressure calculations were shown to compare

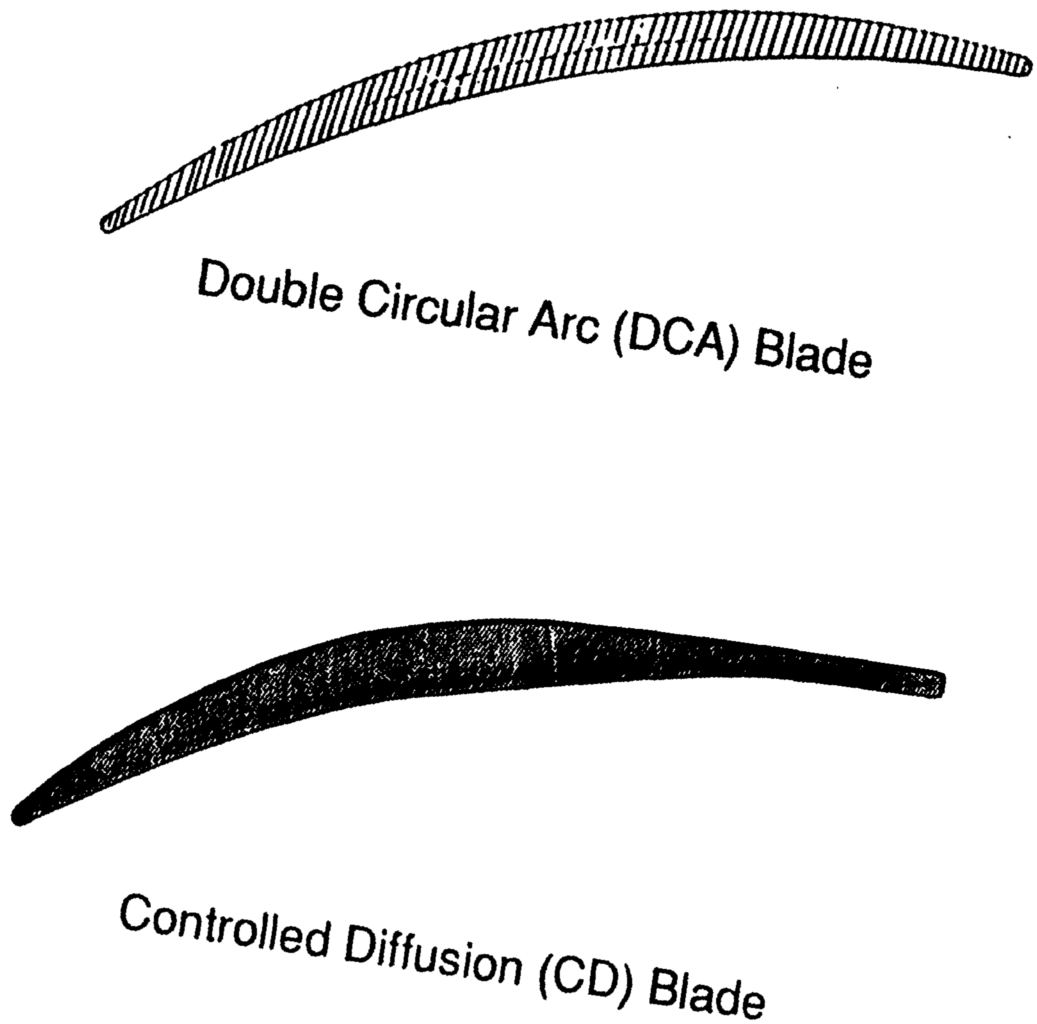

Figure 1. Blade Profiles for CD and DCA Blades

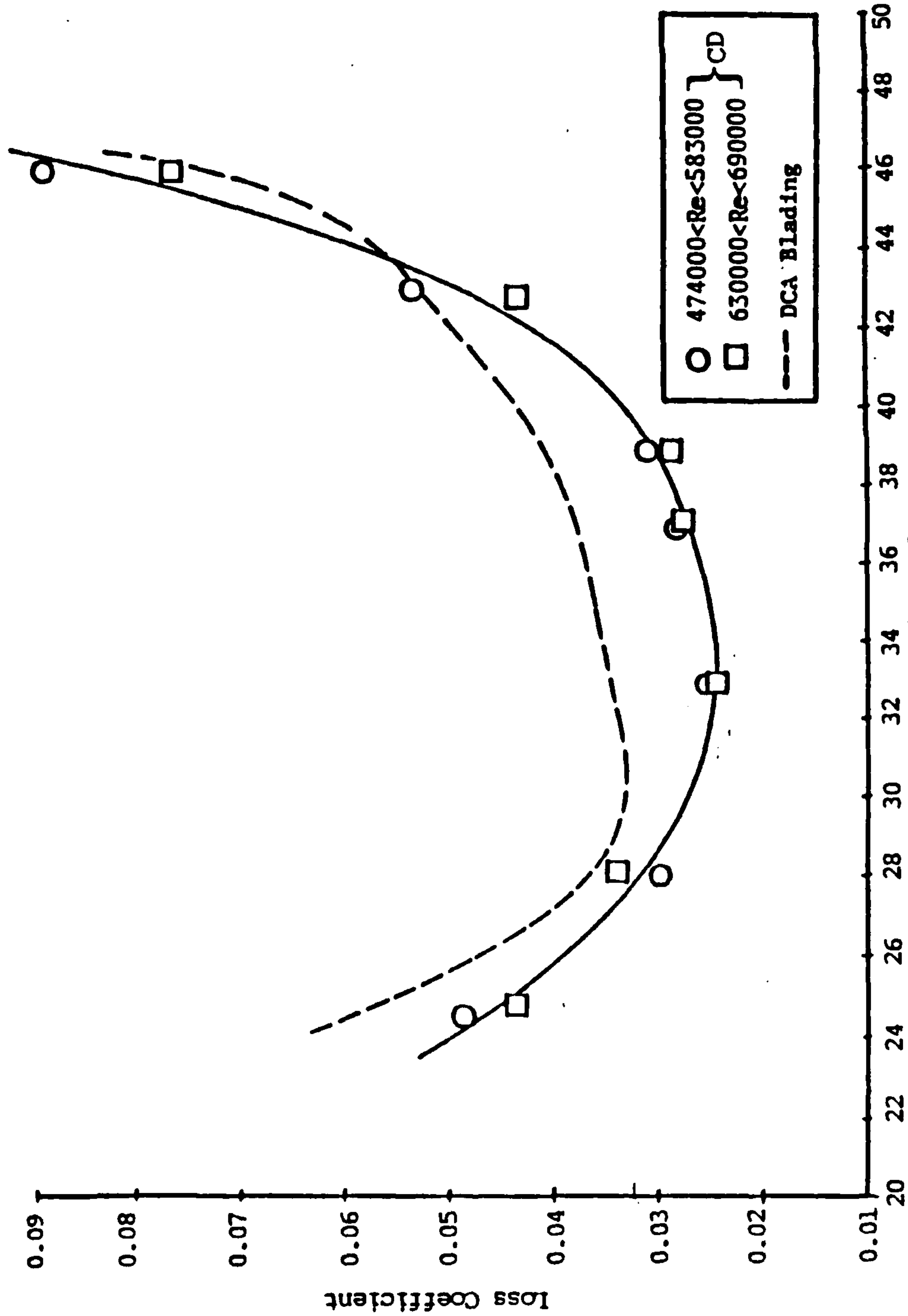

Figure 2. Loss Measurements for CD and DCA Blades

well over the range of inlet flow angles tested(24.49 to 45.96 degrees). However, separation was predicted with less certainty when compared to surface flow visualization using the china clay technique[Ref. 5]. Identified in this attempt to compare results was the clear inability to calculate well off-design, near-stall behavior.

3. Code Validation

A variety of computer methods have been developed to model the flow through axial flow compressors. The more complete quasi-three-dimensional models now include models for secondary flow and case-wall boundary layer effects. However, their basis is usually an interactive solution between an axi-symmetric throughflow and a two-dimensional cascade calculation. The imbedded two-dimensional cascade model of the flow is used to calculate the local blade surface velocity profiles and blade loading, on each stream surface. All computational methods require an experimental database to validate the computer codes and adjust the empirical parameters which are inherent in all viscous flow modeling. For a two-dimensional cascade flow, accurate turbulence and transition models are required to properly predict the behavior at off design conditions, where the flow is largely dominated by viscous effects.

In 1980, when NASA contracted for experiments to be conducted at the U.S. Naval Postgraduate School(NPS) to measure the new CD blading performance, they also initiated work at the Pennsylvania State University(PSU) to obtain validation data for the viscous codes which were necessary in the design process. First results for one incidence angle of 5 degrees on DCA blades using a one-component laser-Doppler velocimetry system on a highly loaded 5 blade cascade were presented by Deutsch and Zierke [Refs. 6, 7, 8].

In 1986, with the importance of stall-prediction identified, Naval Air Systems Command supported the development of viscous-inviscid strong-interaction (SI) codes to provide a cost-effective off-design predictive method for design applications. A parallel program was initiated at NPS to obtain experimental data with which to validate the new SI and existing Navier-Stokes (N-S) codes. Using the CD blading, for which much was already known from the NASA program [Ref. 5], and a newly acquired two-component LDV system, a complete mapping of the cascade flow field was made at design and two higher inlet air angles (40°, 43.4°, and 46°). The complete study was reported by Elazar [Ref. 9], and the viscous flow development sufficient to perform a preliminary code validation was reported by Elazar and Shreeve [Ref. 10]. The results were particularly interesting in the fact that no trailing edge separation was found on the suction side at all three incidence angles, and the flow at the trailing edge was closer to separating at design incidence than at the highest incidence tested. For code validation, these data were highly complimentary with those from PSU which contain trailing edge separation both in the initial results [Refs. 7 and 8] and at the two further incidence angles for which the results were recently described by Deutsch and Zierke [Ref. 11].

B. LASER-DOPPLER VELOCIMETRY AND THE FLOW FIELD

Prior to the studies conducted by Deutsch and Zierke and Elazar, cascade flow studies generally used hot-wire or pressure probe techniques to measure the flow field. The highly undesirable effects of probe disturbance on the boundary layers being measured can be avoided by the use of a laser-Doppler velocimetry (LDV) system. The LDV technique does, however, have some restrictions associated with its use. For example, flow seeding and optical access are required. Absence of flow seeding in the leading edge suction region was a problem for Elazar [Ref. 9].

Deutsch and Zierke were unable to use end wall suction within the passage due to the optical window requirement and were consequently concerned with establishing a proper two-dimensional flow [Ref. 6]. Even with these problems, both studies succeeded in measuring the boundary layer profiles very close to the blade surface over most of the blade passage and showed that LDV was an excellent experimental method for detailed cascade flow studies.

A major unexpected result from Elazar's work was the lack of trailing edge separation found at even the highest flow incidence angle. Sanger and Shreeve reported trailing edge flow separation for flow angles above 38 degrees while Elazar found no evidence of separation. The apparent disagreement was attributed to misinterpretation of the china clay drying patterns or possibly to an effect of Reynolds number, according to Elazar [Ref. 9].

Figure 3 is a diagram of the cascade flow characteristics for CD blades. The leading edge separation bubble on the suction surface was found to extend further along the blade surface at higher incidence angles, reattaching as a turbulent layer. Thus, the transition from laminar to turbulent boundary layers on the suction surface occurred in the free shear layer above the separation bubble. Transition on the pressure surface occurred naturally, at approximately mid-chord. The lack of trailing edge separation on the suction surface was nevertheless off-set by the growth to a very thick boundary layer at the trailing edge (up to 20% blade spacing). [Ref. 9]

C. GOALS AND RESULTS

The primary goal of the present work was to make improvements to the LDV system used by Elazar by installing an automated traverse system and an improved data acquisition and reduction program. While validating the system, a second goal

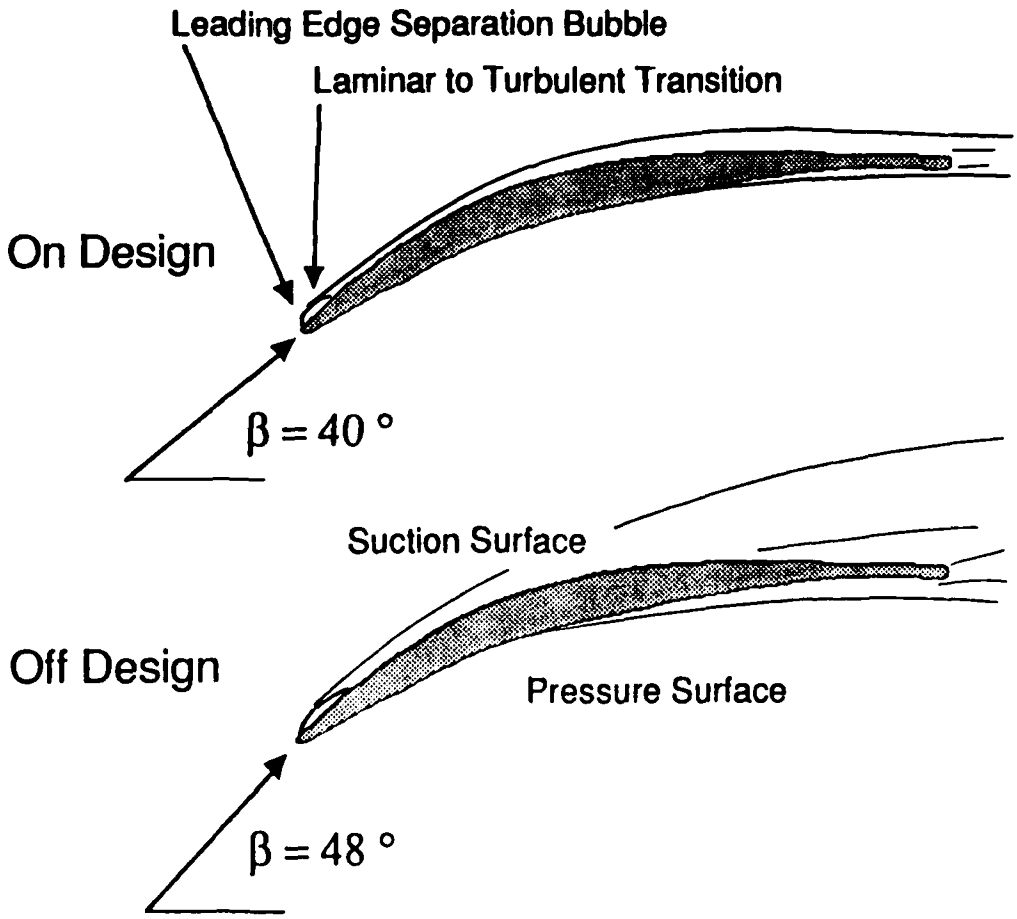

Figure 3. Cascade Flow Characteristics for the CD Blades

was to extend the database collected by Elazar for the CD blade cascade geometry to a higher incidence angle.

A major result of the work was the successful automation of the measurements. The manual traverse (a milling machine table), computer (an HP 1000), and software (DRP3) used by Elazar were replaced by a TSI Model 9500 X-Y-Z traverse table, controlled by an IBM PC/AT computer using the TSI software package FIND. A finely adjustable yaw-plate was added to the table and the synchronized recording of tunnel reference parameters was devised using the laboratory's Hewlett-Packard data acquisition system. Procedures for combining, reducing, and tabulating the data were programmed using IBM PC-based software.

Flow survey data were obtained with the cascade set for an air inlet angle of 48°. Surveys were made of the inlet flow, the flow in the passage, and the flow in the blade wakes. The results are given and discussed in Section III. A description of the apparatus, instrumentation, and techniques, as used for the latest measurements, is given in Section II. A complete user manual for making measurements with the automated system is given on Appendix A.

II. TEST FACILITY, INSTRUMENTATION AND EXPERIMENTAL PROCEDURE

A. ORIGINAL SYSTEM LIMITATIONS

The original LDV system used by Elazar was examined to find any improvements that could be made to the data acquisition process. The following limitations were discovered:

1) The milling machine used for positioning the LDV measuring volume was sensitive to movement direction (hysteresis) and was also physically demanding on the operator during long surveys.
2) The commercial data reduction software, TSI Corporation DRP3, did not store the reduced data in a format easily accessible for post-processing.
3) Results from the data acquisition process were recorded by hand and transferred to the school IBM Mainframe computer by hand for post-processing.
4) TSI Corporation discontinued support for the HP 1000 data acquisition computer interface. New LDV software running on an IBM PC was under development by TSI which would include the capability of recording additional information such as tunnel pressures and temperatures.

These limitations of the existing system led to changes in the data acquisition system and the replacement of the milling machine by an automated three-axis traverse. These system changes are described in more detail in the following sections.

B. SUBSONIC LINEAR CASCADE

The U.S. Naval Postgraduate School Subsonic Cascade Wind Tunnel is a multi-purpose large scale cascade for compressor and turbine research. The configuration for the present work was that reported in Reference 5. A schematic of the wind

tunnel is shown in Figure 4, and the cascade test section configuration is shown in Figures 5 and 6. The CD blade geometry, and coordinate system used to specify the contours are shown in Figure 7. The blade coordinates, cascade geometry, and nominal test conditions are listed in Table I. The tunnel was adjusted for an inlet flow angle of 48 degrees. A detailed description of the tunnel adjustment process and operation is documented in Appendix A.

C. AUTOMATED TRAVERSE TABLE

The automated three-axis traverse is a commercially available Model 9500 from TSI Incorporated and is shown schematically in Figure 8. The traverse uses stepping motors for positioning the optical table which rests between the upper support arms. Digital encoders along each axis provide positioning information to 0.0001 inch (0.00254 mm) accuracy. The traverse and encoder interface to the controlling computer using RS-232C protocol.

LDV surveys close to the blade surface require yawing the optical platform about a vertical axis to allow the measuring volume to be traversed to the blade surface at mid-span without the light beams being 'shadowed' by the blade. Approximately 3.5 degrees of yaw is required since the beams converge at 3.1 degrees to the optical axis. Since no yaw provision existed in the traverse table, the yaw table, shown in Figure 9, was designed and built to permit accurate control of the angle of the platform. The yaw table fits between the traverse mechanism and the optical platform support arms and accommodates up to ±6 degrees of yaw.

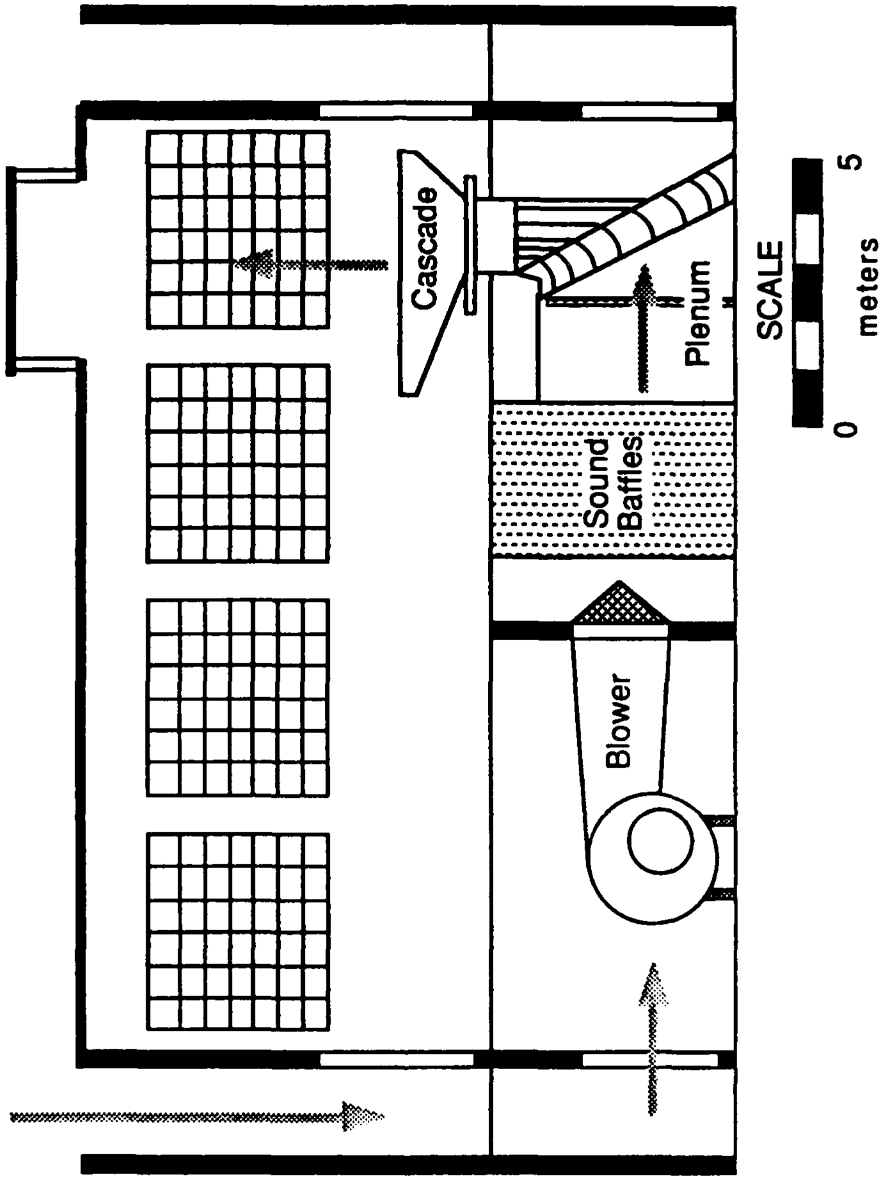

Figure 4. Cascade Wind Tunnel Test Facility

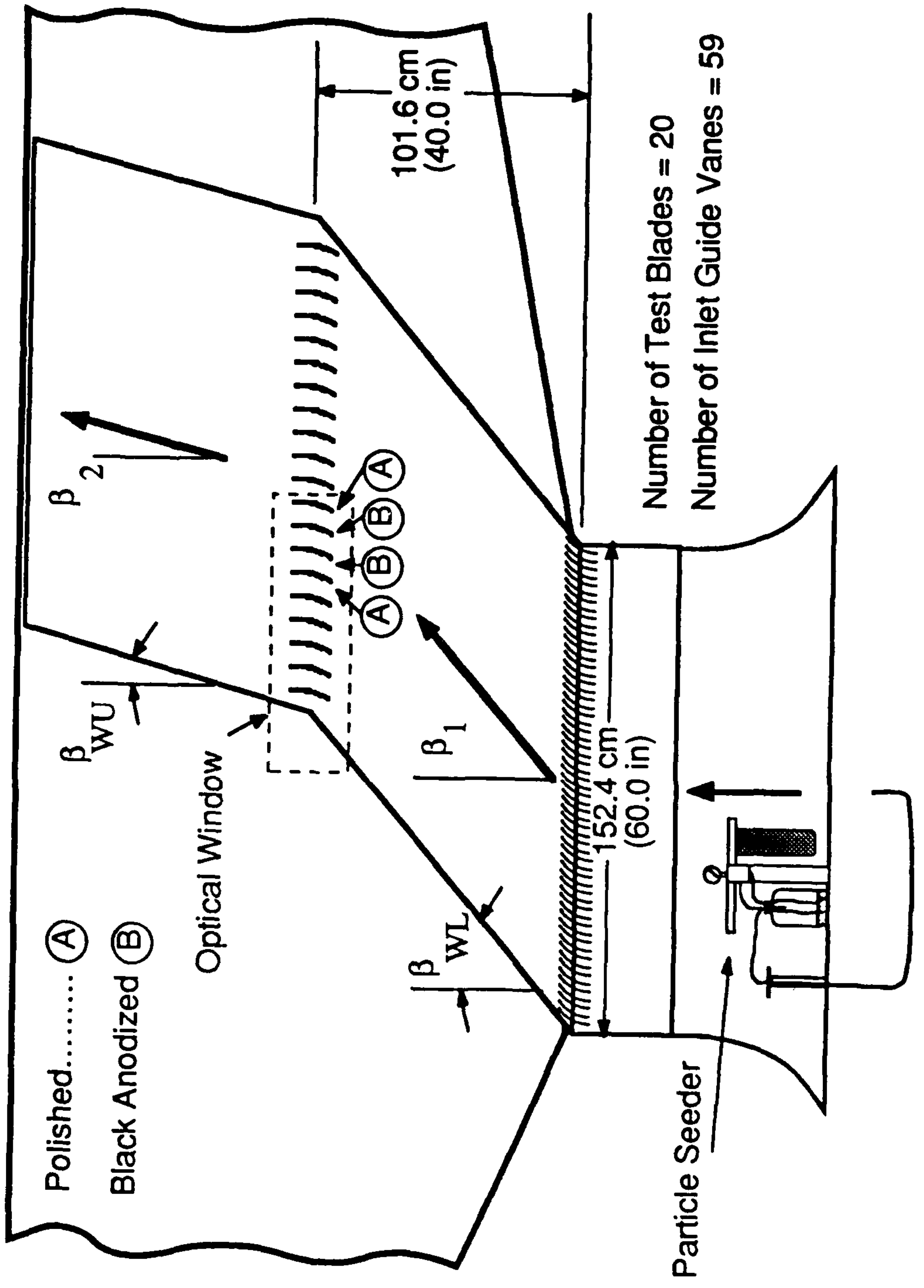

Figure 5. Cascade Wind Tunnel

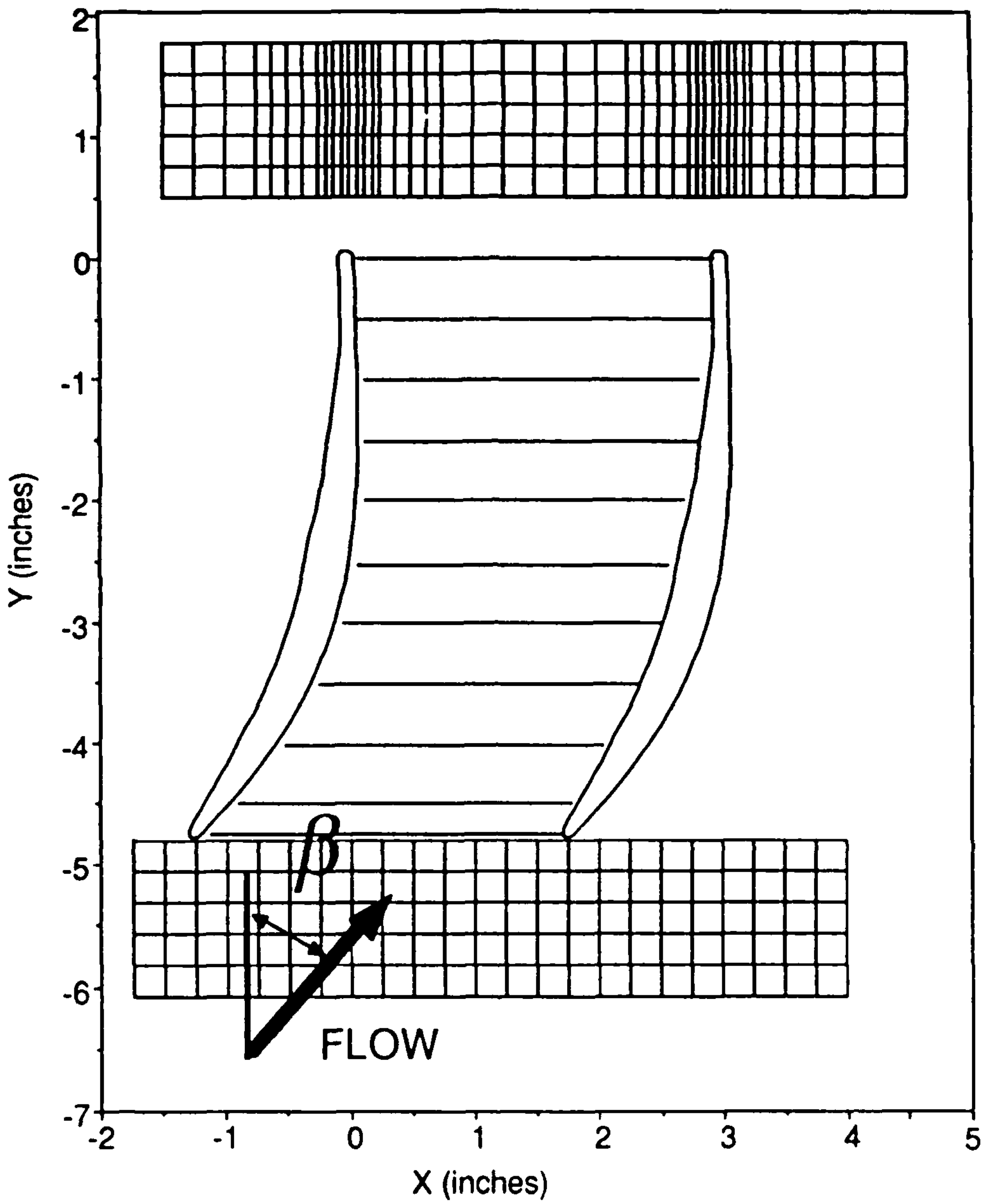

Figure 6. Test Section Passage Geometry and LDV Survey Stations

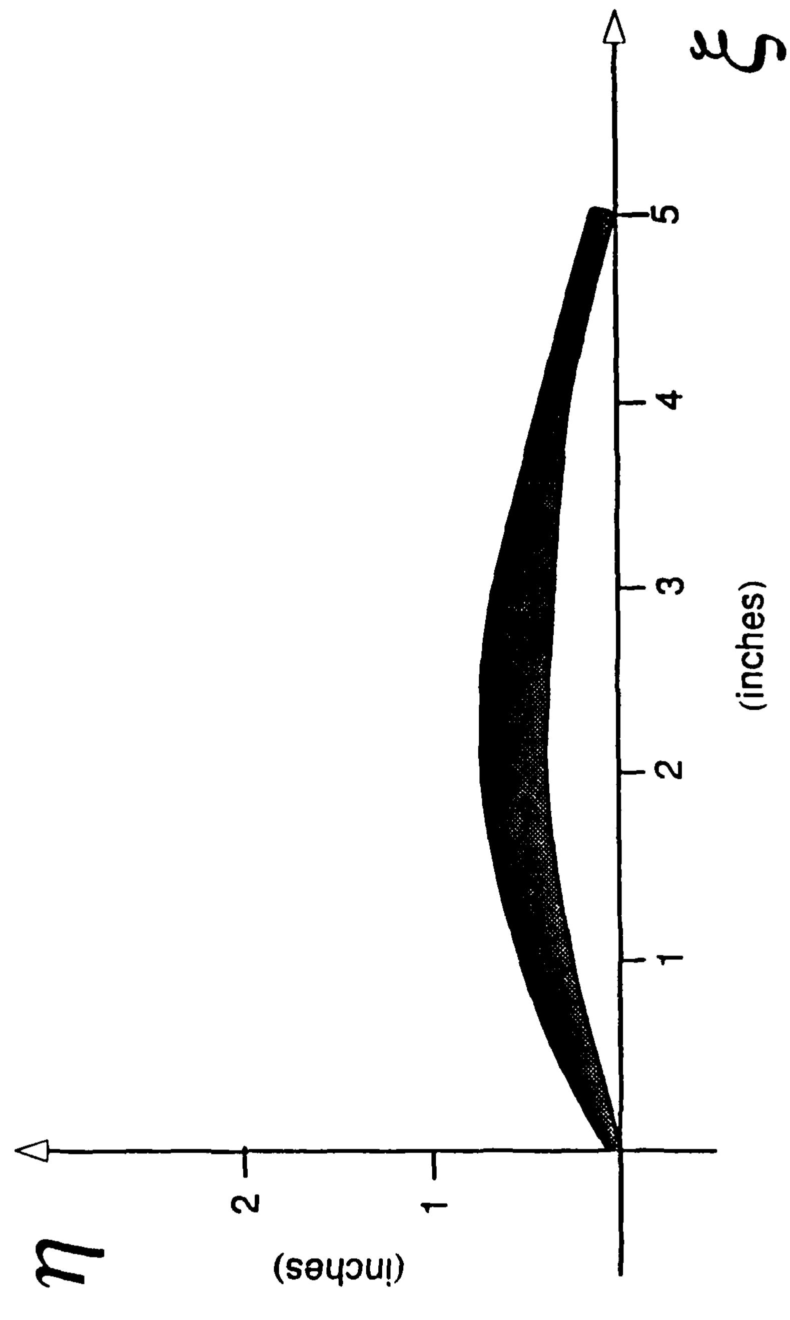

Figure 7. CD Test Blade Geometry

TABLE I. BLADE COORDINATES, CASCADE GEOMETRY, AND NOMINAL TEST CONDITIONS

ξ (inches)	η(pressure side) (inches)	η (suction side) (inches)
0.000	0.045	0.045
0.022	—	0.084
0.057	0.002	—
0.222	0.044	0.196
0.444	0.101	0.307
0.666	0.155	0.403
0.888	0.207	0.488
1.110	0.255	0.561
1.332	0.299	0.621
1.554	0.330	0.663
1.776	0.350	0.691
1.998	0.359	0.705
2.220	0.359	0.708
2.442	0.352	0.701
2.664	0.342	0.681
2.886	0.331	0.650
3.108	0.317	0.610
3.330	0.301	0.563
3.552	0.281	0.510
3.774	0.257	0.453
3.996	0.227	0.393
4.218	0.191	0.332
4.440	0.146	0.270
4.662	0.089	0.208
4.884	0.019	0.145
4.925	0.004	—
4.964	—	0.122
5.010	0.062	0.062

ξ (mm)	η (pressure side) (mm)	η (suction side) (mm)
0.000	0.114	0.114
0.056	—	0.213
0.145	0.005	—
0.564	0.112	0.498
1.128	0.257	0.780
1.692	0.394	1.024
2.256	0.526	1.240
2.819	0.648	1.425
3.383	0.759	1.577
3.947	0.838	1.684
4.511	0.889	1.755
5.075	0.912	1.791
5.639	0.912	1.798
6.203	0.894	1.781
6.767	0.869	1.730
7.330	0.841	1.651
7.894	0.805	1.549
8.458	0.765	1.430
9.022	0.714	1.295
9.586	0.653	1.151
10.150	0.577	0.998
10.714	0.485	0.843
11.278	0.371	0.686
11.841	0.226	0.528
12.405	0.048	0.368
12.510	0.010	—
12.609	—	0.310
12.725	0.157	0.157

Blade Type	Controlled Diffusion
Number of Blades	20
Blade Spacing	7.62 cm
Chord	12.73 cm
Solidity	1.67
Leading Edge Radius	0.114 cm
Trailing Edge Radius	0.157 cm
Thickness	7%
Setting Angle	14.2 ° ± 0.1 °
Stagger Angle	14.4 ° ± 0.1 °
Span	25.40 cm
NOMINAL TEST CONDITIONS	
Reynolds No.(chord)	720,000
Inlet	
Total Temperature	294 K
Total Pressure	1.03 ATM
Mach Number	0.25
Exit	
Static Pressure	1.00 ATM

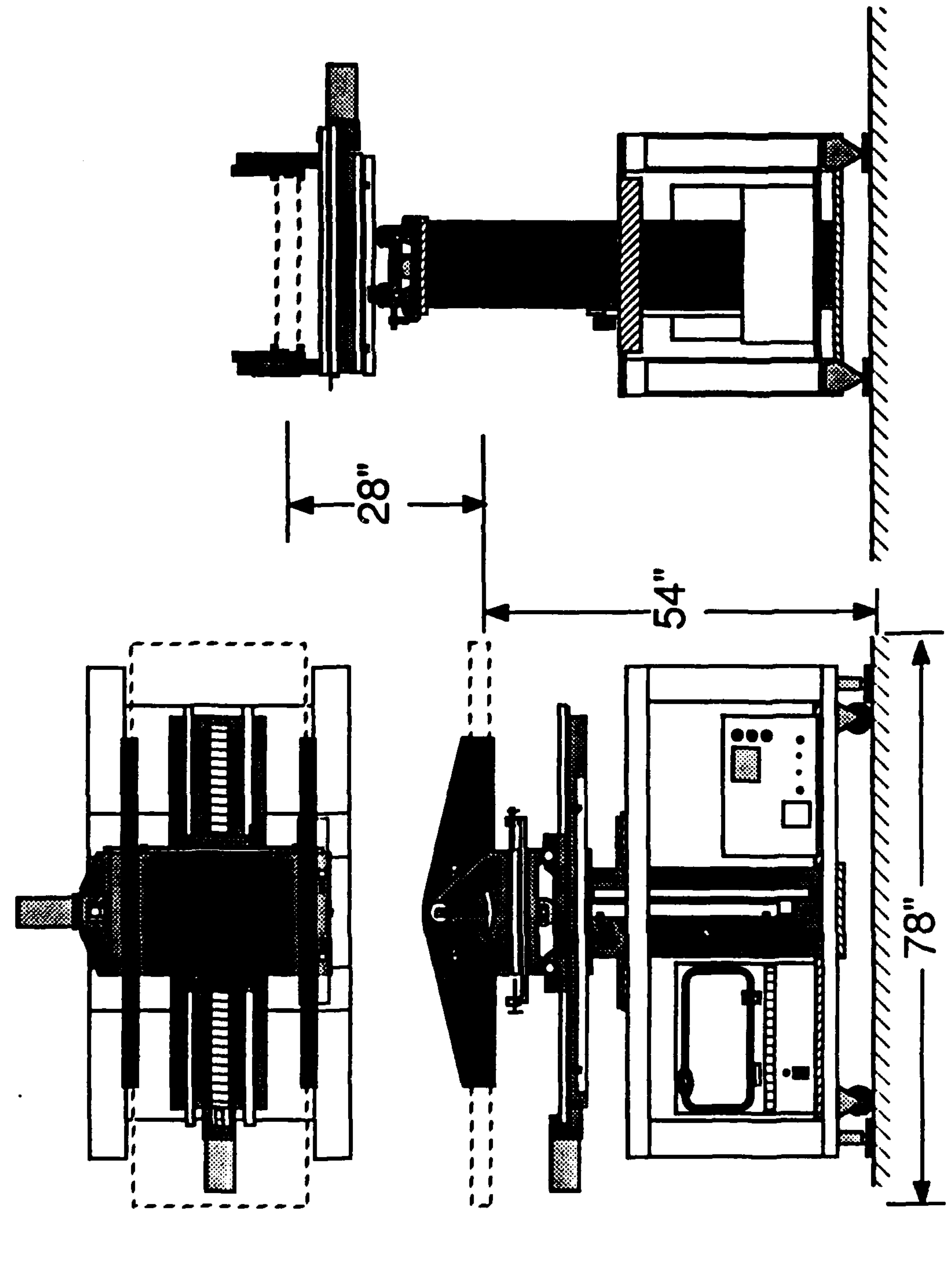

Figure 8. X-Y-Z Automated Traverse Table

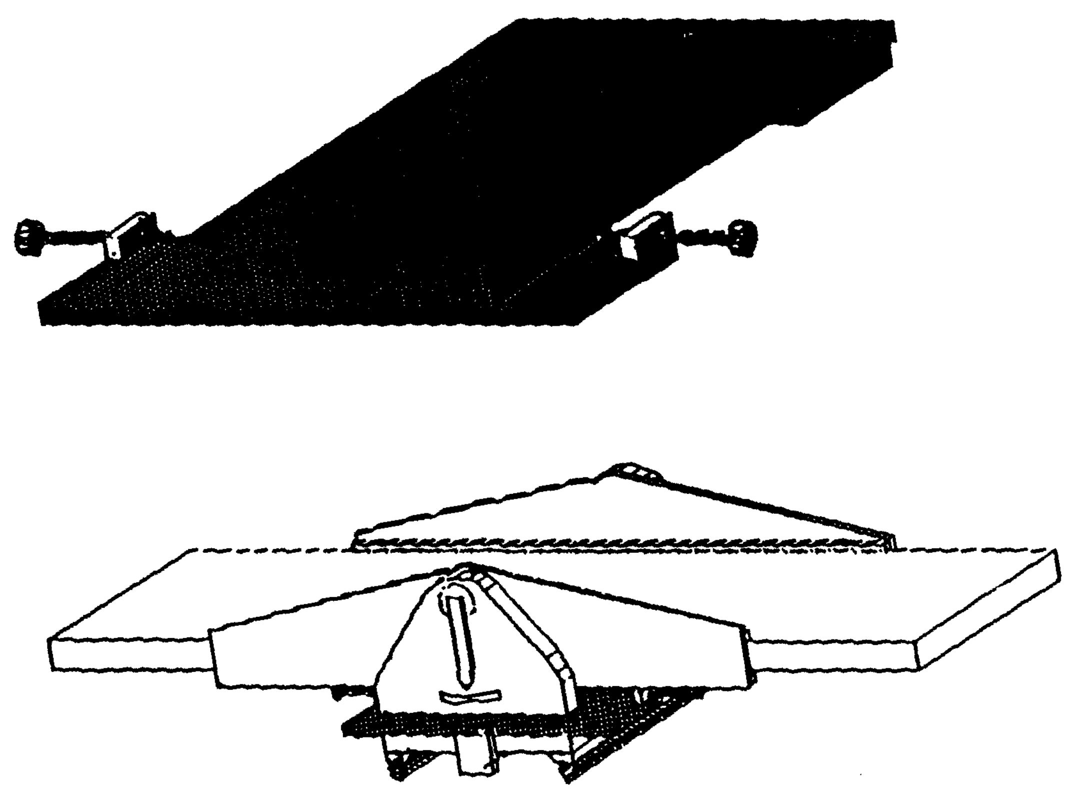

Figure 9. Yaw Table for Traverse Table

D. LDV SYSTEM

A four-beam, two color TSI Model 9100-7 LDV system was used, operating in a dual-beam backscatter mode. Components of the LDV optics are shown in Figure 10. The laser was a Lexel Model 95 4-watt Argon-Ion laser operating nominally at 2 watts. Two wavelengths were used, 488 nm (blue) and 514.5 nm (green), oriented as shown in Figure 11. Frequency shifting was installed using acoustic-optic Bragg cells with downmixing. Photomultipliers were used to collect the Doppler signals. Table II summarizes the LDV system characteristics and estimated measurement uncertainties as given by Elazar [Ref. 9].

LDV signals were processed by two TSI Model 1990 counter-type signal processors as shown schematically in Figure 12. An oscilloscope attached to the input conditioner provided real-time display of the photomultiplier output for setting filters and gain settings. The counters were operated in a single measurement per burst (SM/B), coincident mode. A detailed discussion of counter adjustment is given in Appendix A. A digital interface on each counter provided two functions. First, the master interface compared the incoming signal from each counter and checked for coincidence validation. Secondly, the interface provided computer interface using direct memory access (DMA), sending five 16 bit words for each valid burst to the computer. Typical surveys averaged 1024 readings per position.

E. PARTICLE GENERATOR

The particle generator used for flow seeding was identical to the system reported in Reference 9. A diagram of the system is included in Figure 5. Olive oil was atomized using filtered shop air at 40 psig and then injected into the flow upstream of the test section nozzle contraction. Mean particle size measured by Elazar [Ref 9] was 0.9 μm ($\sigma = 0.45$ μm).

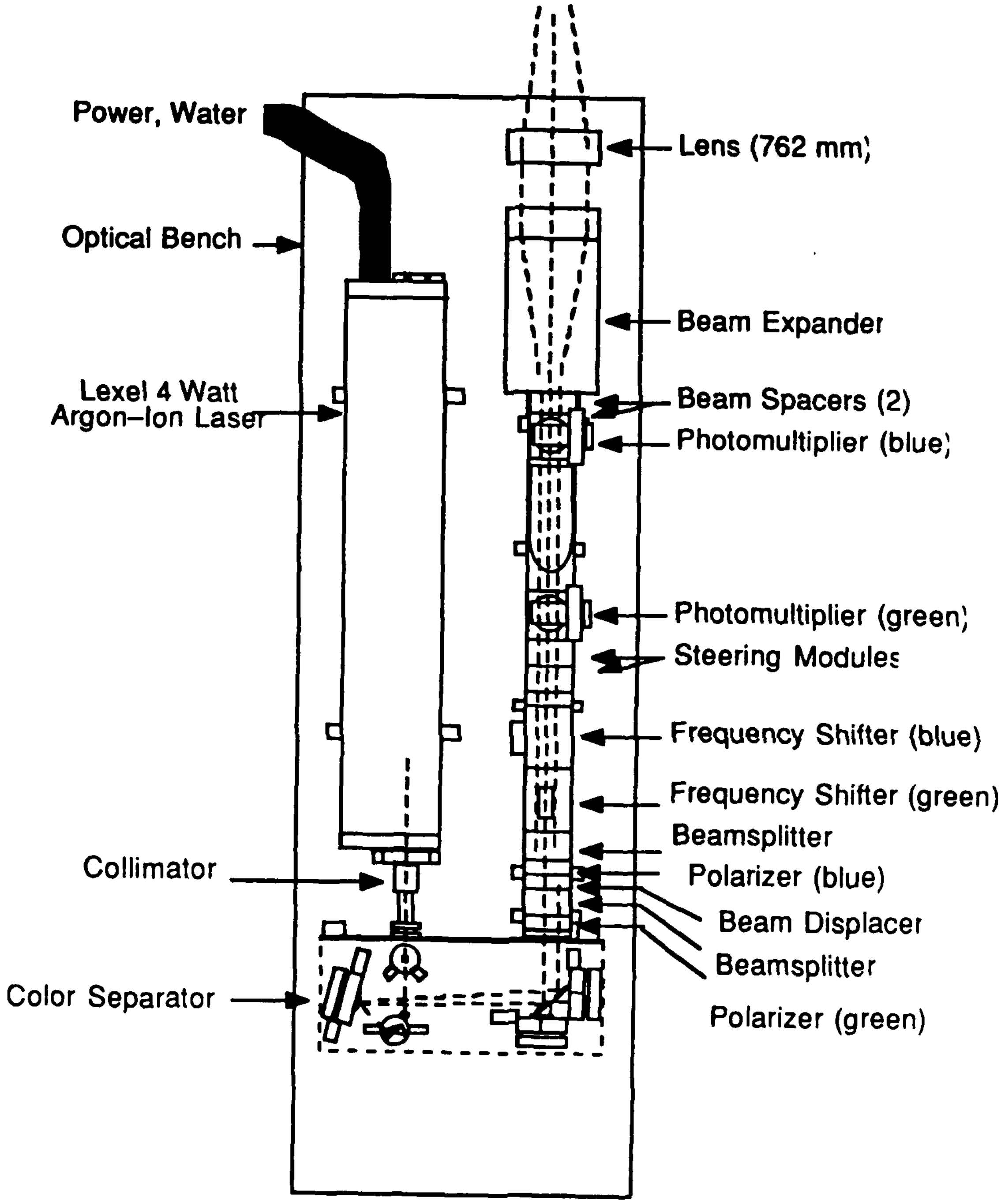

Figure 10. Components of the LDV System Optics

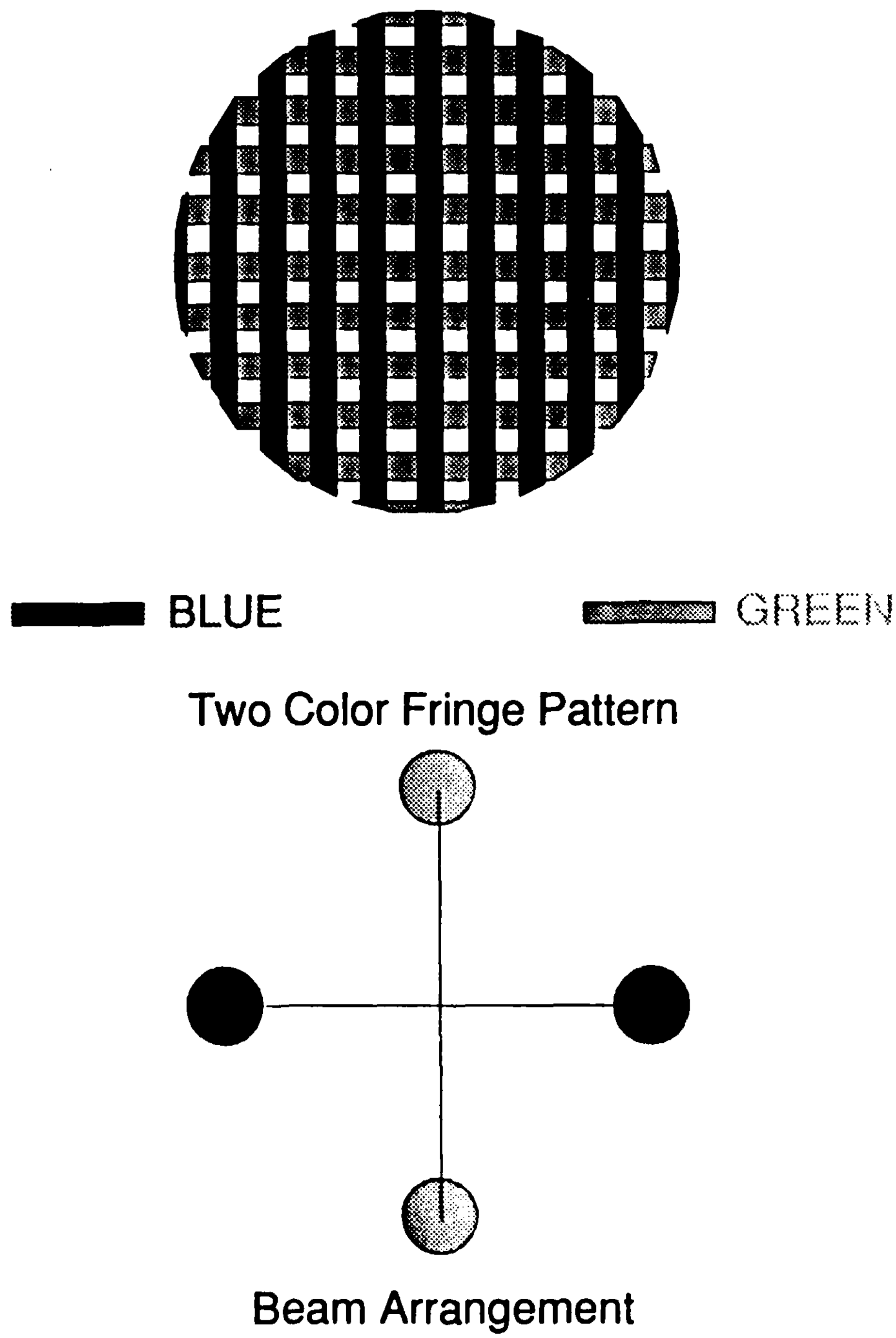

Figure 11. LDV Fringe Pattern and Beam Arrangement

TABLE II. LDV SYSTEM CHARACTERISTICS AND ESTIMATED MEASUREMENT UNCERTAINTIES

LASER		
	Type	Argon-Ion
	Manufacturer	Lexel
	Nominal Power	2.0 watts
WAVELENGTH		
	Blue	488.0 nm
	Green	514.5 nm
FRINGE SPACING		
	Blue	4.51 μm
	Green	4.76 μm
FOCAL LENGTH		762.0 mm
NUMBER OF FRINGES		28
HALF ANGLE		3.1 °
MEASURING VOLUME		
	Length	2.5 mm
	diameter	133.0 μm
FREQUENCY SHIFT		
		2kHz - 40kHz
	Increments	1,2,5,10 MHz
SIGNAL PROCESSOR		
	Type	Counter
	Manufacturer	TSI Mod 1990
COUNTER SETTINGS(typical)		
	Filters	1 - 20 MHz
	Gain	As Required
	Mode	Coincident
		Single Measure/Burst
	cycle / burst	8
	Comparison	7%

Item	Description	Method	Uncertainty
X	Blade-to-Blade (Passage)	Sony Encoder Elec. Readout	0.25 mm
x	Distance from Blade Surface	Sony Encoder Elec. Readout	0.05 mm
Y	Vertical	Sony Encoder Elec. Readout	0.25 mm
y	Distance from Blade Surface	Sony Encoder Elec. Readout	0.05 mm
z	Spanwise	Sony Encoder Elec. Readout	1.25 mm
	Pitch, Roll, Yaw of LDV System	Electronic Level Sperry Model 45	0.1 °
Pp	Plenum Pressure	Scanivalve Transducer	12 Pa
p	Pressure	Scanivalve Transducer	12 Pa
P atm	Atm. Pressure	Mercury Barometer	35 Pa
Tp	Plenum Temp.	Iron Constantan Thermocouple	0.14 °C
	LDV Counter Clock		1 n-sec
K	Beam Half Angle		20 arcsec (0.2%)
L	Focal Length		7.60 mm (1%)
	Wavelength		0.1%
d	Fringe Spacing		0.3%
V	Particle Velocity		0.33% @ 10 m/s 0.65% @ 100 m/s

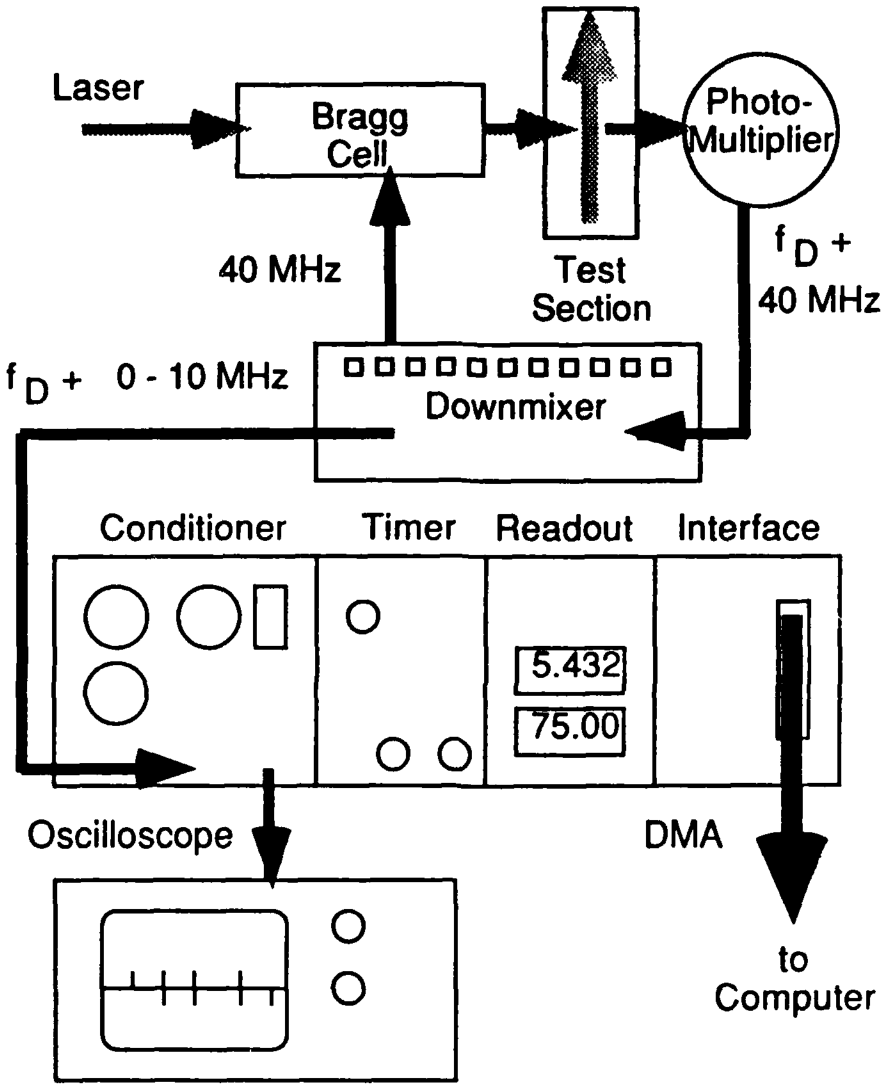

Figure 12. LDV Processing Hardware

F. DATA REDUCTION

Acquisition of the LDV data was controlled by an IBM PC/AT computer using TSI *FIND* software. Tunnel plenum pressure and temperature were recorded concurrently on an HP 9000 series 300 computer and an HP-IB bus. A BASIC language program, *LDVREM*, was written for this purpose. A diagram of the data acquisition hardware is shown in Figure 13. Table III lists the HP-IB port and channel assignments. Data reduction was carried out on the IBM PC/AT using newly generated programs and Lotus 1-2-3. A flow diagram of the data reduction process is shown in Figure 14. Listings of the computer programs developed in-house are given in Appendix B. Appendix A includes a detailed description of the data acquisition and reduction process.

G. DATA NORMALIZATION

Data from the LDV measurements were normalized to account for variations in tunnel operating conditions. An inlet reference flow survey conducted at the beginning of the project was used to develop a simple relationship between tunnel plenum conditions (pressure and temperature) and the inlet flow velocity as measured by the LDV system. Subsequent surveys at other locations in the cascade were then normalized by the inlet reference velocity, V_{ref}, determined by the measured plenum pressure and temperature. Derivation of the equations developed by Elazar [Ref. 9] are summarized in Appendix C.

H. EXPERIMENTAL PROCEDURE

After an extended learning period with the LDV system, four principle survey types were conducted to characterize the cascade flow: inlet reference flow, inlet flow, passage flow, and wake flow surveys. Inlet reference flow, inlet flow, and passage

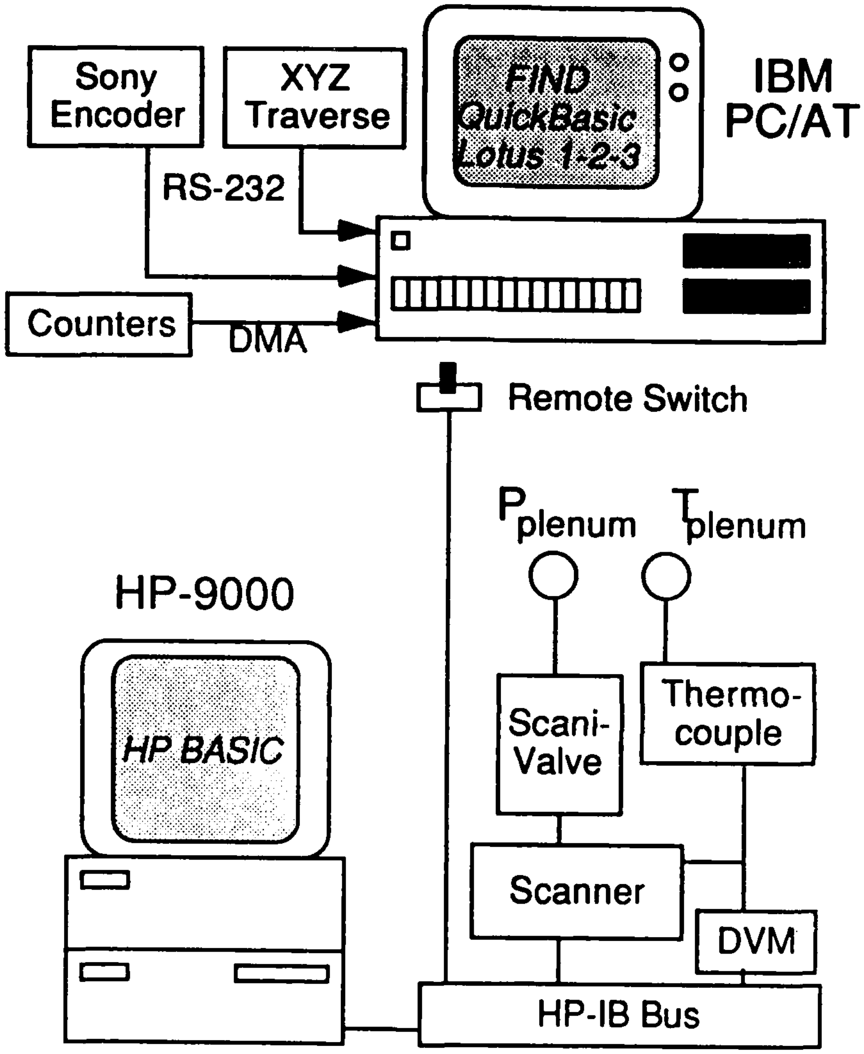

Figure 13. Data Acquisition Hardware

TABLE III. DATA ACQUISITION PORT AND CHANNEL ASSIGNMENTS

7	HP-IB Address
701	Printer
707	Scanivalve Controller
709	Scanner
722	Digital Voltmeter
724	System Voltmeter

# 2	Scanivalve Port Assignments
1	Atmosphere
2	Calibration
3	Plenum

	Scanner Channel Assignments
0	Scanivalve # 1
1	Scanivalve # 2
2	Scanivalve # 3
3	Scanivalve # 4
4	Scanivalve # 5
10	Plenum Temperature (J type)
14	Remote Switch
40	Scanivalve # 1 Step
41	Scanivalve # 2 Step
42	Scanivalve # 3 Step
43	Scanivalve # 4 Step
44	Scanivalve # 5 Step
45	Scanivalve # 1 Reset
46	Scanivalve # 2 Reset
47	Scanivalve # 3 Reset
48	Scanivalve # 4 Reset
49	Scanivalve # 5 Reset
58	Light (Remote in STBY)

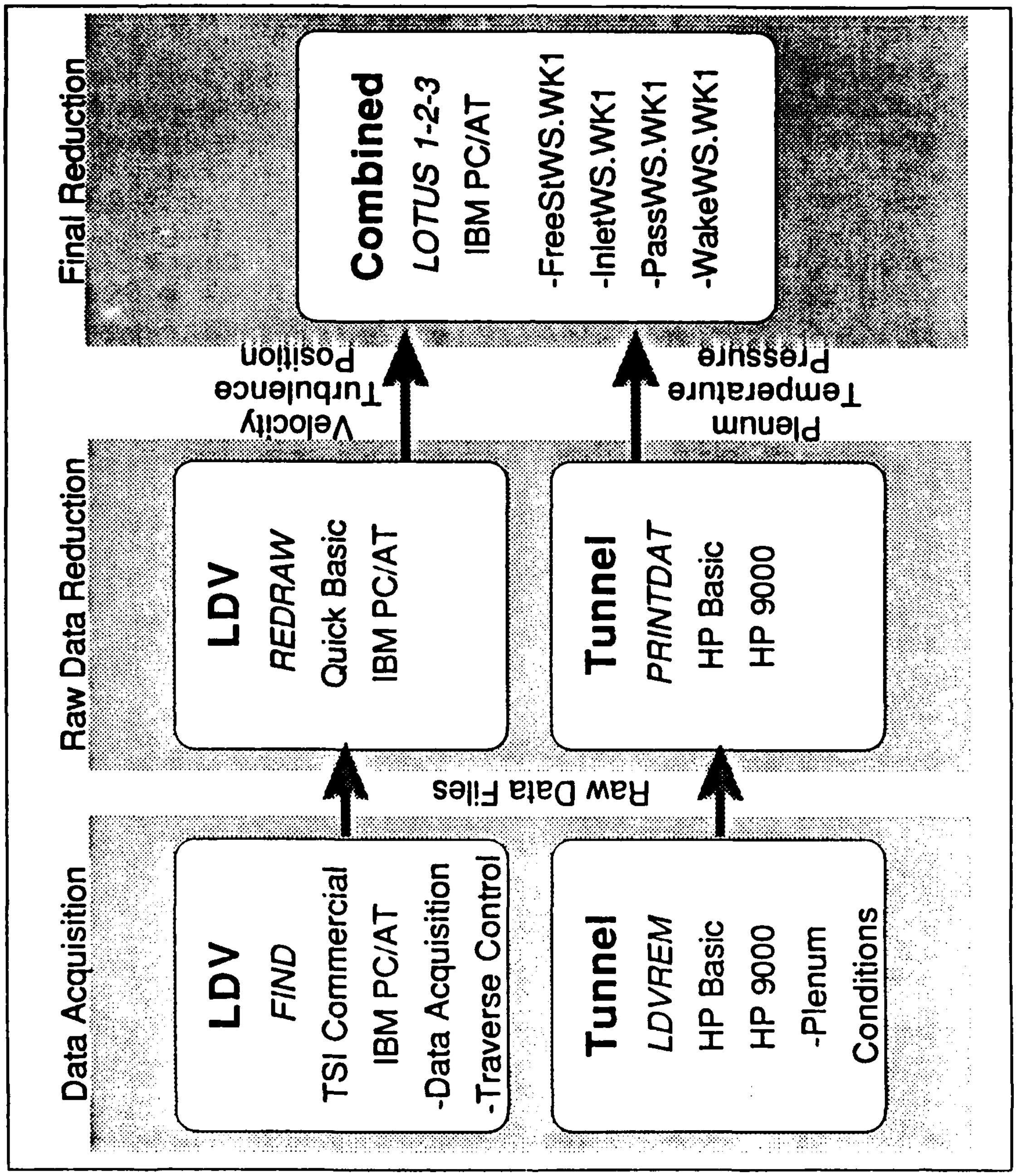

Figure 14. Data Acquisition and Reduction Software Flow Diagram

flow surveys were conducted prior to installation of the traverse table and new data acquisition system described above. Data collection for those surveys were performed as described by Elazar in Reference 9. Wake surveys were conducted using the traverse table and new data acquisition system. The data acquisition and reduction process using the new system is described in Appendix A.

III. RESULTS AND DISCUSSION

Nominal test conditions for all surveys are listed in Table I. Inlet Mach number was about M = 0.25, with a velocity of V_{ref} = 85 m/s. Free stream turbulence intensity was slightly higher than previous inlet flow angle settings, $\varepsilon = 1.76\ \%$ ($\sigma = 0.05$). The increase in turbulence was attributed to the higher incidence settings of the inlet guide vanes.

A. INLET REFERENCE FLOW

Inlet reference flow surveys were conducted at 30.82% axial chord upstream of the blade leading edge. Frequency shifting was not used. Inlet reference flow surveys were used during tunnel adjustment to ensure uniform inlet flow angle and velocity. A final survey was then used to determine the reference velocity normalizing loss coefficient, C_{p12}, as described in Appendix C.

Results of the inlet flow reference survey are given in Table IV and in Figures 15 and 16. Blade-to-blade location was normalized by blade spacing, with the origin located at the leading edge of blade 7. A setting of 49.5mm on the inlet guide vanes (IGV) was found to be optimal for an average uniform inlet flow angle of 48 degrees. The reference velocity normalizing loss coefficient determined from the flow survey was calculated as $C_{p12} = 0.7364$.

TABLE IV. INLET REFERENCE SURVEY

Final	Freestream Output
Date	3/2/89
Lotus File	F0302001
Beta (deg)	48.00
STA (inches)	1.50 from LE
STA (% chord)	30.82%
Patm (in Hg)	29.80
Re_c	720569
Normalizing:	Origin: Leading Edge Blade 7
Velocity	Vref
Turbulence	Vref
X station	spacing
Y station	axial chord

Run	X (% spacing)	u/Vref	v/Vref	V/Vref	turb_tot (%)	Alpha (deg)	Beta (deg)
1	-58.71%	0.7471	0.6767	1.0080	1.66%	42.17	47.83
2	-50.38%	0.7425	0.6762	1.0043	1.75%	42.32	47.68
3	-42.05%	0.7387	0.6715	0.9983	1.76%	42.27	47.73
4	-33.71%	0.7359	0.6678	0.9937	1.76%	42.22	47.78
5	-25.38%	0.7345	0.6641	0.9902	1.72%	42.12	47.88
6	-17.05%	0.7335	0.6614	0.9877	1.73%	42.04	47.96
7	-8.71%	0.7370	0.6623	0.9908	1.71%	41.95	48.05
8	-0.38%	0.7402	0.6608	0.9922	1.83%	41.75	48.25
9	7.95%	0.7463	0.6632	0.9985	1.76%	41.63	48.37
10	16.29%	0.7484	0.6660	1.0018	1.80%	41.67	48.33
11	24.62%	0.7510	0.6715	1.0074	1.71%	41.80	48.20
12	32.95%	0.7497	0.6757	1.0092	1.76%	42.03	47.97
13	41.29%	0.7475	0.6792	1.0100	1.72%	42.26	47.74
14	49.62%	0.7431	0.6785	1.0063	1.87%	42.40	47.60
15	57.95%	0.7403	0.6778	1.0037	1.82%	42.48	47.52
16	66.29%	0.7392	0.6765	1.0021	1.73%	42.46	47.54
17	74.62%	0.7413	0.6730	1.0012	1.78%	42.24	47.76
						Average: (from X= -2 to +1)	47.94

Intermediate Freestream Output

Run	X (in)	u (m/s)	v (m/s)	V (m/s)	Turb_loc (%)	Pp Patm Patm	Xv	nu(Xv)	Cp_12	Xv	Vref (m/s)
1	-3.000	63.37	57.40	85 50	1.66%	0.0306	0.1116	0.0422	0.7251	0.1107	84 82
2	-2.750	62.98	57.36	85.18	1.75%	0.0306	0.1111	0.0419	0.7303	0.1107	84.82
3	-2.500	62.78	57.07	84.85	1.76%	0.0307	0.1107	0.0416	0.7388	0.1109	84.99
4	-2 250	62.55	56.76	84.46	1.77%	0.0307	0.1102	0.0412	0.7454	0.1109	84.99
5	-2.000	62 58	56.58	84.36	1.74%	0.0309	0.1100	0.0411	0.7506	0.1111	85 20
6	-1.750	62 63	56.46	84.32	1.75%	0.0310	0.1100	0.0411	0.7543	0.1114	85.37
7	-1.500	62.92	56.54	84.59	1.73%	0.0310	0.1103	0.0413	0.7497	0.1114	85 37
8	-1.250	63.27	56.48	84.81	1.84%	0.0310	0.1106	0.0415	0.7476	0.1115	85 48
9	-1.000	63.85	56.74	85.42	1.77%	0.0311	0.1114	0.0421	0.7386	0 1116	85 55
10	-0.750	64.16	57.10	85 88	1.79%	0.0312	0.1120	0.0426	0.7338	0.1118	85 72
11	-0.500	64.38	57.57	86.36	1.69%	0.0312	0.1126	0.0430	0.7259	0.1118	85 72
12	-0.250	64.40	58.04	86 69	1.75%	0.0313	0.1131	0.0433	0.7234	0.1120	85 90
13	0.000	64.21	58.35	86 76	1.70%	0 0313	0.1132	0.0434	0.7224	0.1120	85 90
14	0.250	63 83	58.28	86 44	1.86%	0.0313	0.1127	0 0431	0.7275	0.1120	85 90
15	0.500	63.64	58.27	86.29	1.81%	0 0314	0.1125	0.0429	0.7311	0 1121	85 97
16	0.750	63 63	58.23	86 25	1.73%	0.0315	0.1125	0.0429	0.7334	0 1123	86 07
17	1.000	63.80	57.93	86.18	1.78%	0.0315	0.1124	0.0428	0.7347	0.1123	86.07
								Average Cp_12 (from X= -2 to +1)	0.7364		

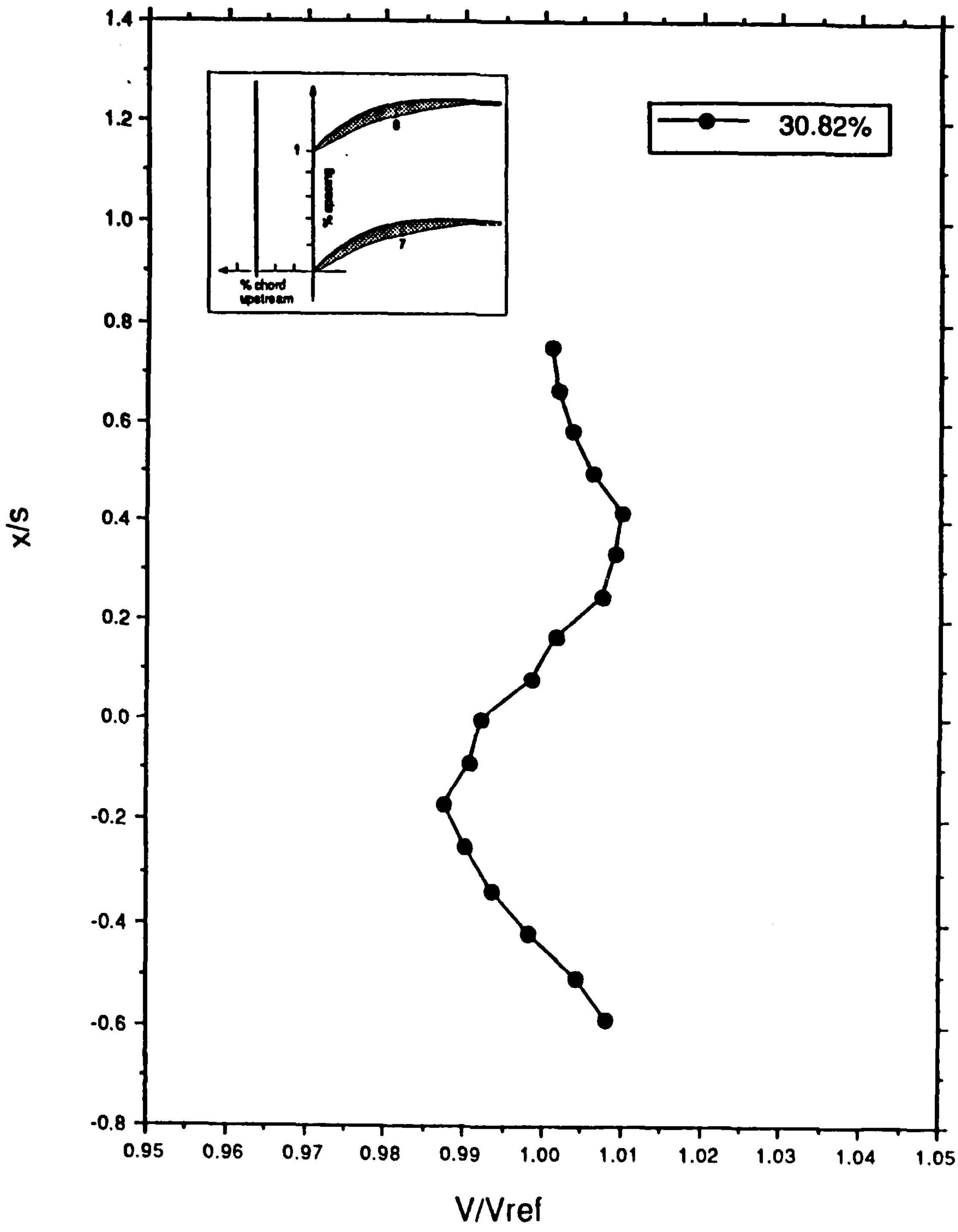

Figure 15. Inlet Reference Survey: Velocity Profile

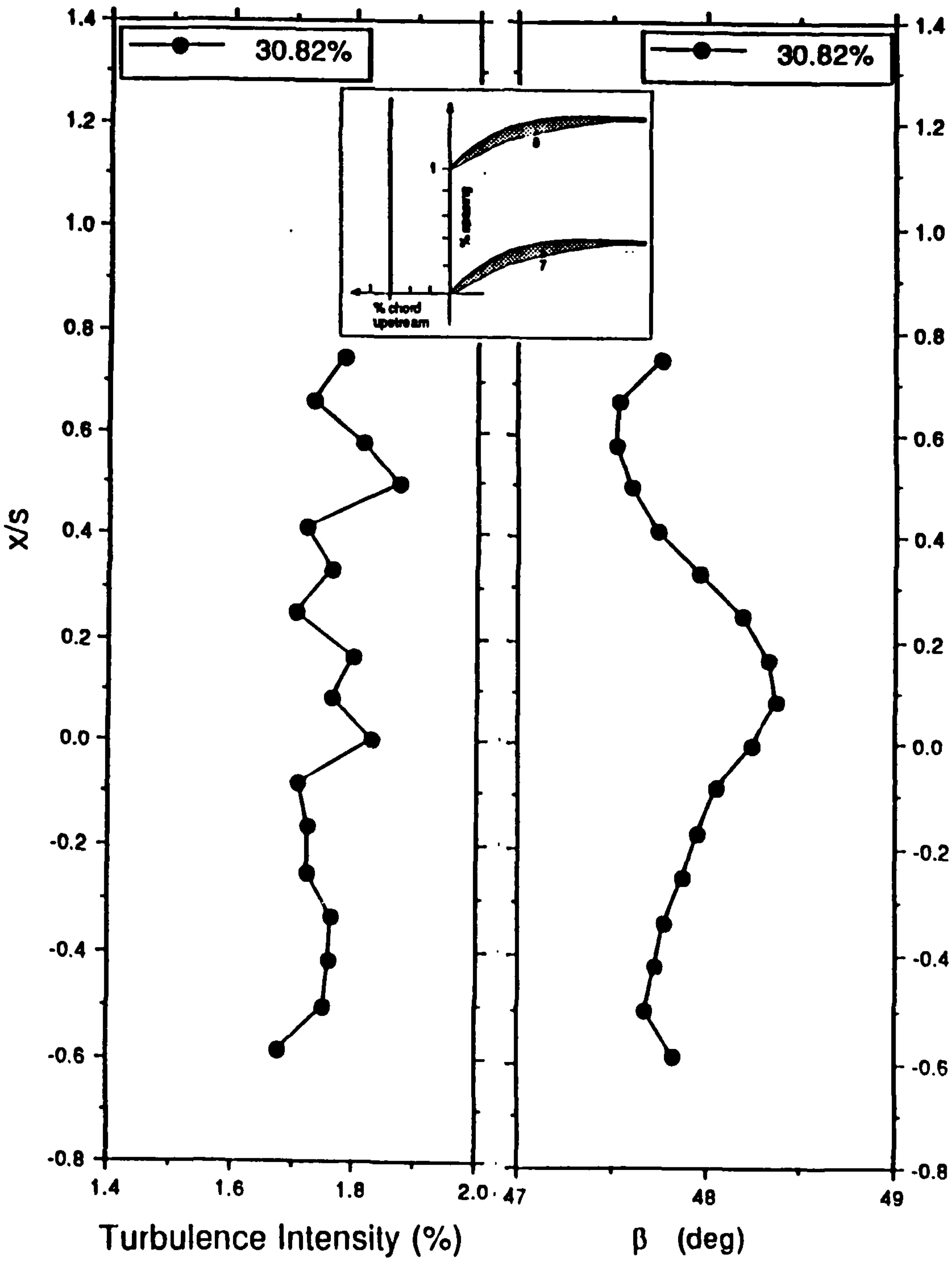

Figure 16. Inlet Reference Survey: Turbulence Intensity and Flow Angle Profiles

Seen in Figures 15 and 16 was the noticeable upstream influence of the blades. However, the velocity across 1 1/2 blade spaces was found to deviate less than 2% from the average. Flow angle across the span deviated from the average by about 0.5 degrees. Turbulence intensity was approximately uniform across the span. Surveys much further from the passage inlet were not possible due to the limited size of the optical window.

B. INLET FLOW

Inlet flow surveys were made to map the flow entering the blade passage. Flow surveys at eight stations upstream of the leading edge were conducted, 1.13% to 37.17% of axial chord. Frequency shifting was not used. Yaw was used only for the survey at 1.13% axial chord when blade interference was a problem. The results for the eight surveys are given in Tables V through XII. To improve clarity, only every other survey has been plotted in Figures 17-19.

Normalized velocity versus blade-to-blade position is shown in Figure 17. Acceleration around the suction surface leading edge was evident, especially in the survey at 1.13% axial chord where the velocity ratio peaked at 1.25.

Turbulence intensity versus blade-to-blade position is shown in Figure 18. Turbulence intensity rose slightly but remained uniform up to about 20% axial chord upstream. The rise in turbulence intensity near the leading edge peaks at about 6% at the same location of the peak in velocity ratio. The peak appeared to define the development of the free shear layer as described by Elazar [Ref. 9].

Flow angle versus blade-to-blade position is shown in Figure 19. Streamline curvature was seen to develop progressively as the leading edge was approached and reached a peak of 75 degrees near the leading edge.

TABLE V. INLET SURVEY: 1.13% AXIAL CHORD UPSTREAM OF BLADE LEADING EDGE

Final	Inlet Output		
Date	3/29/89		
Lotus File	I0329001		
Beta (deg)	48.00		
STA (inches)	0.06 from LE		
STA (% chord)	1.13%		
Patm (in Hg)	30.24		
Re_c	726666		
Normalizing:		Origin:	Leading Edge Blade 7
Velocity	Vref		
Turbulence	Vref		
X station	spacing		
Y station	axial chord		

Run	X (% spacing)	u/Vref	v/Vref	V/Vref	turb_tot (%)	Alpha (deg)	Beta (deg)
1	-50.38%	0.6821	0.7735	1.0312	3.07%	48.59	41.41
2	-42.05%	0.6495	0.7414	0.9857	2.59%	48.78	41.22
3	-33.71%	0.6256	0.7030	0.9411	2.36%	48.33	41.67
4	-25.38%	0.6102	0.6602	0.8990	2.08%	47.26	42.74
5	-17.05%	0.5950	0.6034	0.8474	1.74%	45.40	44.60
6	-11.38%	0.5962	0.5323	0.7992	2.26%	41.76	48.24
7	-0.05%	0.8675	0.2335	0.8984	4.95%	15.06	74.94
8	0.12%	0.8439	0.2351	0.8761	5.03%	15.57	74.43
9	0.29%	0.8733	0.2355	0.9045	4.89%	15.09	74.91
10	0.45%	0.8929	0.2373	0.9239	4.98%	14.88	75.12
11	0.62%	0.9121	0.2358	0.9420	5.08%	14.50	75.50
12	1.29%	0.9954	0.2780	1.0335	5.98%	15.61	74.39
13	4.62%	1.0961	0.4959	1.2030	5.83%	24.34	65.66
14	7.95%	1.0680	0.6506	1.2505	5.02%	31.35	58.65
15	11.29%	1.0163	0.7310	1.2519	4.83%	35.73	54.27
16	14.62%	0.9655	0.7741	1.2375	4.36%	38.72	51.28
17	16.29%	0.9402	0.7880	1.2267	4.25%	39.97	50.03
18	24.62%	0.8380	0.8179	1.1710	4.27%	44.31	45.69
19	32.95%	0.7757	0.8103	1.1217	4.29%	46.25	43.75
20	41.29%	0.7180	0.7906	1.0680	4.21%	47.75	42.25
21	49.62%	0.6732	0.7641	1.0184	3.33%	48.62	41.38
22	57.95%	0.6402	0.7346	0.9744	2.62%	48.93	41.07
23	66.29%	0.6183	0.6967	0.9315	2.45%	48.41	41.59
24	74.62%	0.6047	0.6532	0.8902	2.06%	47.21	42.79

TABLE VI. INLET SURVEY: 6.28% AXIAL CHORD UPSTREAM OF BLADE LEADING EDGE

Final	Inlet Output		
Date	3/27/89		
Lotus File	I0327004		
Beta (deg)	48.00		
STA (inches)	0.31 from LE		
STA (% chord)	6.28%		
Patm (in Hg)	30.15		
Re_c	716657		
Normalizing:		Origin:	Leading Edge Blade 7
Velocity	Vref		
Turbulence	Vref		
X station	spacing		
Y station	axial chord		

Run	X (% spacing)	u/Vref	v/Vref	V/Vref	turb_tot (%)	Alpha (deg)	Beta (deg)
1	-50.38%	0.7147	0.7501	1.0361	2.50%	46.38	43.62
2	-42.05%	0.6929	0.7318	1.0077	2.59%	46.56	43.44
3	-33.71%	0.6718	0.7029	0.9724	2.31%	46.30	43.70
4	-25.38%	0.6616	0.6680	0.9402	2.26%	45.28	44.72
5	-17.05%	0.6642	0.6255	0.9123	2.09%	43.28	46.72
6	-8.71%	0.6907	0.5825	0.9035	1.79%	40.14	49.86
7	-0.38%	0.7704	0.5587	0.9517	2.04%	35.95	54.05
8	7.95%	0.8735	0.6045	1.0623	2.35%	34.69	55.31
9	16.29%	0.8799	0.6869	1.1163	2.98%	37.98	52.02
10	24.62%	0.8304	0.7359	1.1095	3.12%	41.55	48.45
11	32.95%	0.7876	0.7499	1.0876	3.57%	43.59	46.41
12	41.29%	0.7405	0.7498	1.0538	2.98%	45.36	44.64
13	49.62%	0.7015	0.7348	1.0159	2.87%	46.33	43.67
14	57.95%	0.6755	0.7173	0.9853	2.76%	46.72	43.28
15	66.29%	0.6613	0.6877	0.9540	2.60%	46.12	43.88
16	74.62%	0.6548	0.6551	0.9262	2.51%	45.01	44.99
17	82.95%	0.6605	0.6169	0.9038	2.15%	43.04	46.96
18	91.29%	0.6947	0.5729	0.9005	2.09%	39.51	50.49
19	99.62%	0.7925	0.5544	0.9672	2.05%	34.98	55.02

TABLE VII. INLET SURVEY: 11.43% AXIAL CHORD UPSTREAM OF BLADE LEADING EDGE

Final	Inlet Output		
Date	3/27/89		
Lotus File	I0327003		
Beta (deg)	48.00		
STA (inches)	0.56 from LE		
STA (% chord)	11.43%		
Patm (in Hg)	30.15		
Re_c	716657		
Normalizing:		Origin:	Leading Edge Blade 7
Velocity	Vref		
Turbulence	Vref		
X station	spacing		
Y station	axial chord		

Run	X (% spacing)	u/Vref	v/Vref	V/Vref	turb_tot (%)	Alpha (deg)	Beta (deg)
1	-50.38%	0.7211	0.7220	1.0204	2.48%	45.04	44.96
2	-42.05%	0.7012	0.7027	0.9927	2.56%	45.06	44.94
3	-33.71%	0.6877	0.6828	0.9691	2.31%	44.80	45.20
4	-25.38%	0.6870	0.6582	0.9514	2.29%	43.77	46.23
5	-17.05%	0.6953	0.6320	0.9396	2.15%	42.27	47.73
6	-8.71%	0.7210	0.6098	0.9443	1.87%	40.22	49.78
7	-0.38%	0.7652	0.6045	0.9752	2.09%	38.31	51.69
8	7.95%	0.8065	0.6277	1.0220	2.28%	37.89	52.11
9	16.29%	0.8171	0.6660	1.0541	2.83%	39.18	50.82
10	24.62%	0.8010	0.7034	1.0661	2.99%	41.29	48.71
11	32.95%	0.7769	0.7150	1.0559	3.46%	42.62	47.38
12	41.29%	0.7441	0.7205	1.0358	2.93%	44.08	45.92
13	49.62%	0.7228	0.7129	1.0152	2.87%	44.61	45.39
14	57.95%	0.7022	0.7025	0.9933	2.79%	45.01	44.99
15	66.29%	0.6919	0.6810	0.9708	2.65%	44.54	45.46
16	74.62%	0.6879	0.6596	0.9531	2.59%	43.80	46.20
17	82.95%	0.6999	0.6334	0.9439	2.25%	42.15	47.85
18	91.29%	0.7289	0.6154	0.9539	2.21%	40.17	49.83
19	99.62%	0.7758	0.6144	0.9897	2.12%	38.38	51.62

TABLE VIII. INLET SURVEY: 16.58% AXIAL CHORD UPSTREAM OF BLADE LEADING EDGE

Final	Inlet Output	
Date	3/27/89	
Lotus File	I0327002	
Beta (deg)	48.00	
STA (inches)	0.81 from LE	
STA (% chord)	16.58%	
Patm (in Hg)	30.14	
Re_c	715036	
Normalizing:		Origin: Leading Edge Blade 7
Velocity	Vref	
Turbulence	Vref	
X station	spacing	
Y station	axial chord	

Run	X (% spacing)	u/Vref	v/Vref	V/Vref	turb_tot (%)	Alpha (deg)	Beta (deg)
1	-50.38%	0.7292	0.7041	1.0137	2.30%	44.00	46.00
2	-42.05%	0.7162	0.6944	0.9975	2.24%	44.11	45.89
3	-33.71%	0.7091	0.6787	0.9816	2.22%	43.74	46.26
4	-25.38%	0.7059	0.6635	0.9688	2.12%	43.23	46.77
5	-17.05%	0.7117	0.6467	0.9616	2.12%	42.26	47.74
6	-8.71%	0.7265	0.6362	0.9657	2.17%	41.21	48.79
7	-0.38%	0.7508	0.6352	0.9835	2.18%	40.23	49.77
8	7.95%	0.7737	0.6463	1.0082	2.16%	39.87	50.13
9	16.29%	0.7824	0.6654	1.0271	2.67%	40.38	49.62
10	24.62%	0.7782	0.6833	1.0356	2.47%	41.29	48.71
11	32.95%	0.7662	0.6945	1.0341	2.64%	42.19	47.81
12	41.29%	0.7480	0.6970	1.0224	2.84%	42.98	47.02
13	49.62%	0.7310	0.6978	1.0106	2.60%	43.67	46.33
14	57.95%	0.7218	0.6904	0.9988	2.29%	43.73	46.27
15	66.29%	0.7156	0.6793	0.9867	2.36%	43.51	46.49
16	74.62%	0.7157	0.6619	0.9748	2.51%	42.76	47.24
17	82.95%	0.7264	0.6467	0.9726	2.27%	41.68	48.32
18	91.29%	0.7430	0.6414	0.9815	2.20%	40.81	49.19
19	99.62%	0.7690	0.6408	1.0010	2.36%	39.81	50.19

TABLE IX. INLET SURVEY: 21.72% AXIAL CHORD UPSTREAM OF BLADE LEADING EDGE

Final	Inlet Output		
Date	3/27/89		
Lotus File	I0327001		
Beta (deg)	48.00		
STA (inches)	1.06 from LE		
STA (% chord)	21.72%		
Patm (in Hg)	30.13		
Re_c	721662		
Normalizing:		Origin:	Leading Edge Blade 7
Velocity	Vref		
Turbulence	Vref		
X station	spacing		
Y station	axial chord		

Run	X (% spacing)	u/Vref	v/Vref	V/Vref	turb_tot (%)	Alpha (deg)	Beta (deg)
1	-50.38%	0.7410	0.6920	1.0139	1.79%	43.04	46.96
2	-42.05%	0.7315	0.6842	1.0016	1.90%	43.09	46.91
3	-33.71%	0.7242	0.6759	0.9906	2.12%	43.02	46.98
4	-25.38%	0.7226	0.6640	0.9814	1.98%	42.58	47.42
5	-17.05%	0.7278	0.6551	0.9792	2.03%	41.99	48.01
6	-8.71%	0.7379	0.6489	0.9827	2.14%	41.33	48.67
7	-0.38%	0.7487	0.6490	0.9908	2.24%	40.92	49.08
8	7.95%	0.7600	0.6566	1.0044	2.06%	40.82	49.18
9	16.29%	0.7630	0.6658	1.0127	2.31%	41.11	48.89
10	24.62%	0.7616	0.6794	1.0206	2.31%	41.74	48.26
11	32.95%	0.7548	0.6904	1.0229	2.41%	42.45	47.55
12	41.29%	0.7459	0.6914	1.0171	2.40%	42.83	47.17
13	49.62%	0.7364	0.6906	1.0096	2.40%	43.16	46.84
14	57.95%	0.7295	0.6866	1.0018	2.31%	43.26	46.74
15	66.29%	0.7291	0.6779	0.9956	2.27%	42.92	47.08
16	74.62%	0.7293	0.6704	0.9906	2.20%	42.59	47.41
17	82.95%	0.7356	0.6611	0.9890	2.21%	41.95	48.05
18	91.29%	0.7487	0.6581	0.9968	2.22%	41.32	48.68
19	99.62%	0.7602	0.6597	1.0066	2.41%	40.95	49.05

TABLE X. INLET SURVEY: 26.87% AXIAL CHORD UPSTREAM OF BLADE LEADING EDGE

Final	Inlet Output		
Date	3/10/89		
Lotus File	I0310002		
Beta (deg)	48.00		
STA (inches)	1.31 from LE		
STA (% chord)	26.87%		
Patm (in Hg)	30.12		
Re_c	718930		
Normalizing:		Origin:	Leading Edge Blade 7
Velocity	Vref		
Turbulence	Vref		
X station	spacing		
Y station	axial chord		

Run	X (% spacing)	u/Vref	v/Vref	V/Vref	turb_tot (%)	Alpha (deg)	Beta (deg)
1	-50.38%	0.7439	0.6799	1.0078	1.83%	42.43	47.57
2	-42.05%	0.7397	0.6765	1.0024	1.82%	42.45	47.55
3	-33.71%	0.7380	0.6704	0.9970	1.91%	42.25	47.75
4	-25.38%	0.7334	0.6668	0.9912	1.85%	42.28	47.72
5	-17.05%	0.7363	0.6606	0.9892	1.87%	41.90	48.10
6	-8.71%	0.7413	0.6582	0.9914	1.76%	41.60	48.40
7	-0.38%	0.7464	0.6591	0.9958	2.00%	41.44	48.56
8	7.95%	0.7526	0.6626	1.0027	2.07%	41.36	48.64
9	16.29%	0.7579	0.6685	1.0106	1.96%	41.41	48.59
10	24.62%	0.7582	0.6742	1.0146	2.03%	41.64	48.36
11	32.95%	0.7536	0.6796	1.0147	2.14%	42.04	47.96
12	41.29%	0.7490	0.6824	1.0132	2.15%	42.34	47.66
13	49.62%	0.7454	0.6821	1.0104	2.09%	42.46	47.54
14	57.95%	0.7407	0.6800	1.0056	2.14%	42.55	47.45
15	66.29%	0.7376	0.6767	1.0010	2.01%	42.53	47.47
16	74.62%	0.7378	0.6731	0.9987	2.14%	42.38	47.62
17	82.95%	0.7439	0.6750	1.0045	2.14%	42.22	47.78
18	91.29%	0.7517	0.6656	1.0040	2.16%	41.53	48.47
19	99.62%	0.7613	0.6690	1.0135	2.04%	41.31	48.69

TABLE XI. INLET SURVEY: 32.02% AXIAL CHORD UPSTREAM OF BLADE LEADING EDGE

Final	Inlet Output		
Date	3/10/89		
Lotus File	I0310001		
Beta (deg)	48.00		
STA (inches)	1.56 from LE		
STA (% chord)	32.02%		
Patm (in Hg)	30.12		
Re_c	727380		
Normalizing:		Origin:	Leading Edge Blade 7
Velocity	Vref		
Turbulence	Vref		
X station	spacing		
Y station	axial chord		

Run	X (% spacing)	u/Vref	v/Vref	V/Vref	turb_tot (%)	Alpha (deg)	Beta (deg)
1	-50.38%	0.7477	0.6807	1.0111	1.65%	42.32	47.68
2	-42.05%	0.7443	0.6777	1.0066	1.73%	42.32	47.68
3	-33.71%	0.7402	0.6733	1.0006	1.94%	42.29	47.71
4	-25.38%	0.7401	0.6682	0.9971	1.83%	42.08	47.92
5	-17.05%	0.7410	0.6662	0.9964	1.81%	41.96	48.04
6	-8.71%	0.7425	0.6625	0.9951	1.89%	41.74	48.26
7	-0.38%	0.7481	0.6614	0.9986	1.95%	41.48	48.52
8	7.95%	0.7537	0.6650	1.0051	1.93%	41.42	48.58
9	16.29%	0.7547	0.6661	1.0066	1.98%	41.43	48.57
10	24.62%	0.7543	0.6698	1.0087	2.03%	41.61	48.39
11	32.95%	0.7554	0.6748	1.0130	2.03%	41.78	48.22
12	41.29%	0.7522	0.6811	1.0148	1.96%	42.16	47.84
13	49.62%	0.7460	0.6818	1.0106	1.94%	42.43	47.57
14	57.95%	0.7445	0.6783	1.0071	2.03%	42.34	47.66
15	66.29%	0.7449	0.6767	1.0064	1.90%	42.26	47.74
16	74.62%	0.7468	0.6731	1.0054	1.96%	42.03	47.97
17	82.95%	0.7534	0.6700	1.0082	2.01%	41.65	48.35
18	91.29%	0.7569	0.6746	1.0139	1.82%	41.71	48.29
19	99.62%	0.7624	0.6740	1.0176	2.02%	41.48	48.52

TABLE XII. INLET SURVEY: 37.17% AXIAL CHORD UPSTREAM OF BLADE LEADING EDGE

Final	Inlet Output		
Date	3/3/89		
Lotus File	I0303001		
Beta (deg)	48.00		
STA (inches)	1.81 from LE		
STA (% chord)	37.17%		
Patm (In Hg)	29.80		
Re_c	721695		
Normalizing:		Origin:	Leading Edge Blade 7
Velocity	Vref		
Turbulence	Vref		
X station	spacing		
Y station	axial chord		

Run	X (% spacing)	u/Vref	v/Vref	V/Vref	turb_tot (%)	Alpha (deg)	Beta (deg)
1	-50.38%	0.7375	0.6716	0.9975	1.75%	42.32	47.68
2	-42.05%	0.7365	0.6722	0.9972	1.82%	42.38	47.62
3	-33.71%	0.7368	0.6711	0.9966	1.83%	42.33	47.67
4	-25.38%	0.7374	0.6664	0.9939	1.80%	42.11	47.89
5	-17.05%	0.7370	0.6654	0.9930	1.74%	42.08	47.92
6	-8.71%	0.7380	0.6625	0.9918	1.80%	41.91	48.09
7	-0.38%	0.7411	0.6641	0.9951	1.73%	41.86	48.14
8	7.95%	0.7442	0.6643	0.9975	1.92%	41.76	48.24
9	16.29%	0.7474	0.6657	1.0009	1.97%	41.69	48.31
10	24.62%	0.7476	0.6684	1.0028	1.93%	41.80	48.20
11	32.95%	0.7496	0.6730	1.0074	1.97%	41.92	48.08
12	41.29%	0.7449	0.6776	1.0070	1.91%	42.29	47.71
13	49.62%	0.7404	0.6768	1.0031	1.87%	42.43	47.57
14	57.95%	0.7409	0.6759	1.0029	2.10%	42.38	47.62
15	66.29%	0.7430	0.6748	1.0037	2.02%	42.25	47.75
16	74.62%	0.7440	0.6743	1.0041	2.04%	42.18	47.82
17	82.95%	0.7487	0.6737	1.0072	2.04%	41.98	48.02
18	91.29%	0.7519	0.6740	1.0098	2.15%	41.87	48.13
19	99.62%	0.7551	0.6759	1.0135	2.00%	41.83	48.17

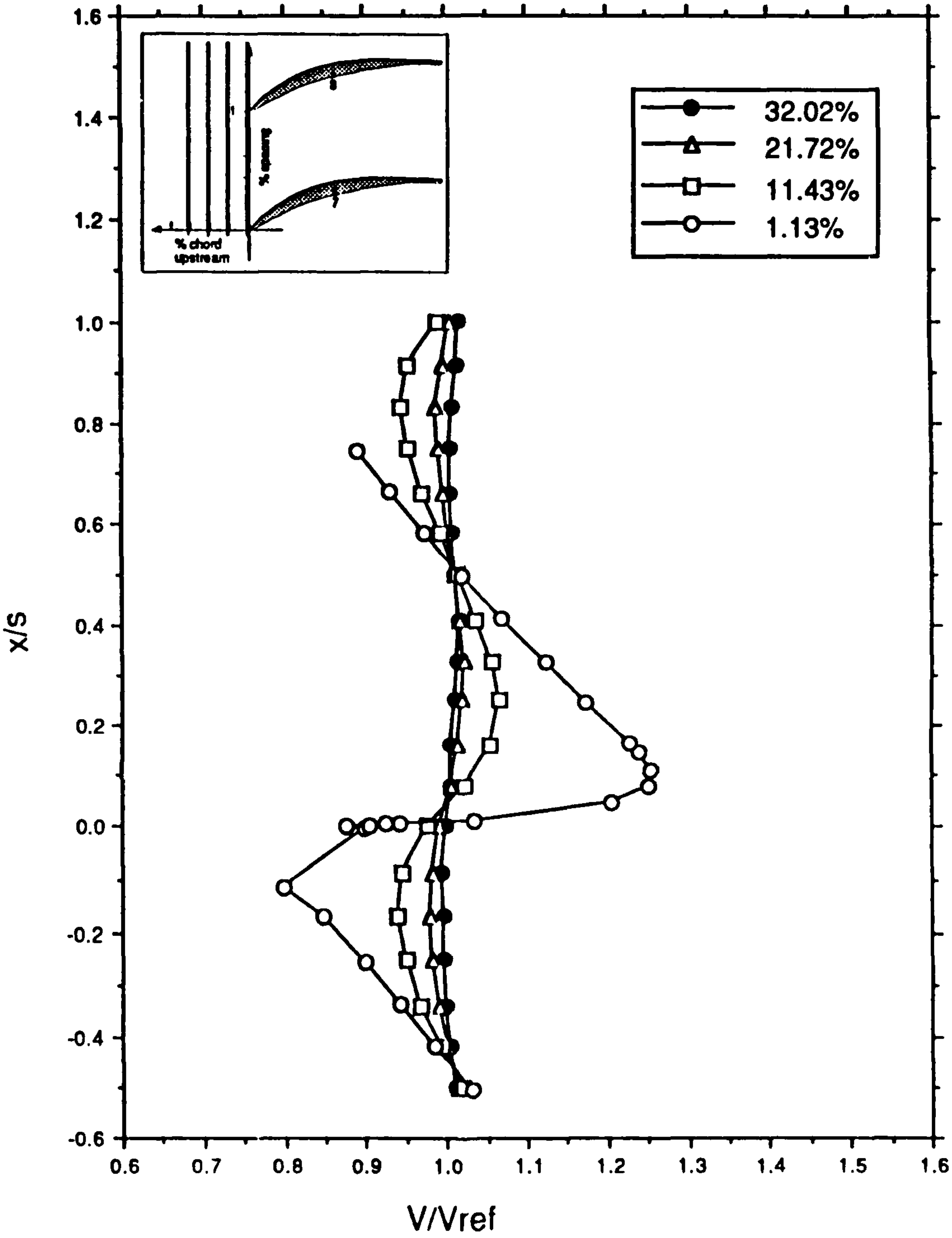

Figure 17. Inlet Flow Survey: Velocity Profiles

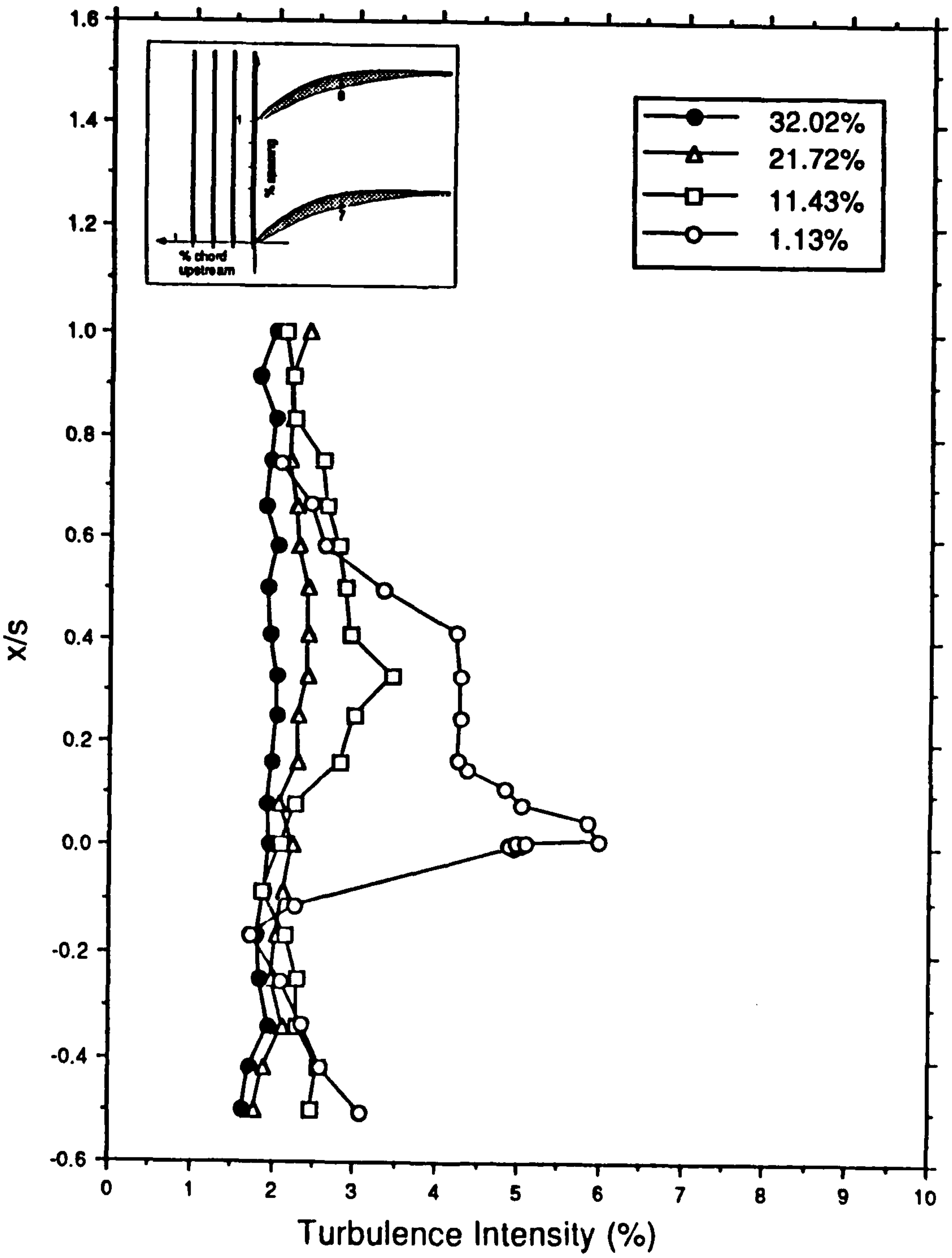

Figure 18. Inlet Flow Survey: Turbulence Intensity Profiles

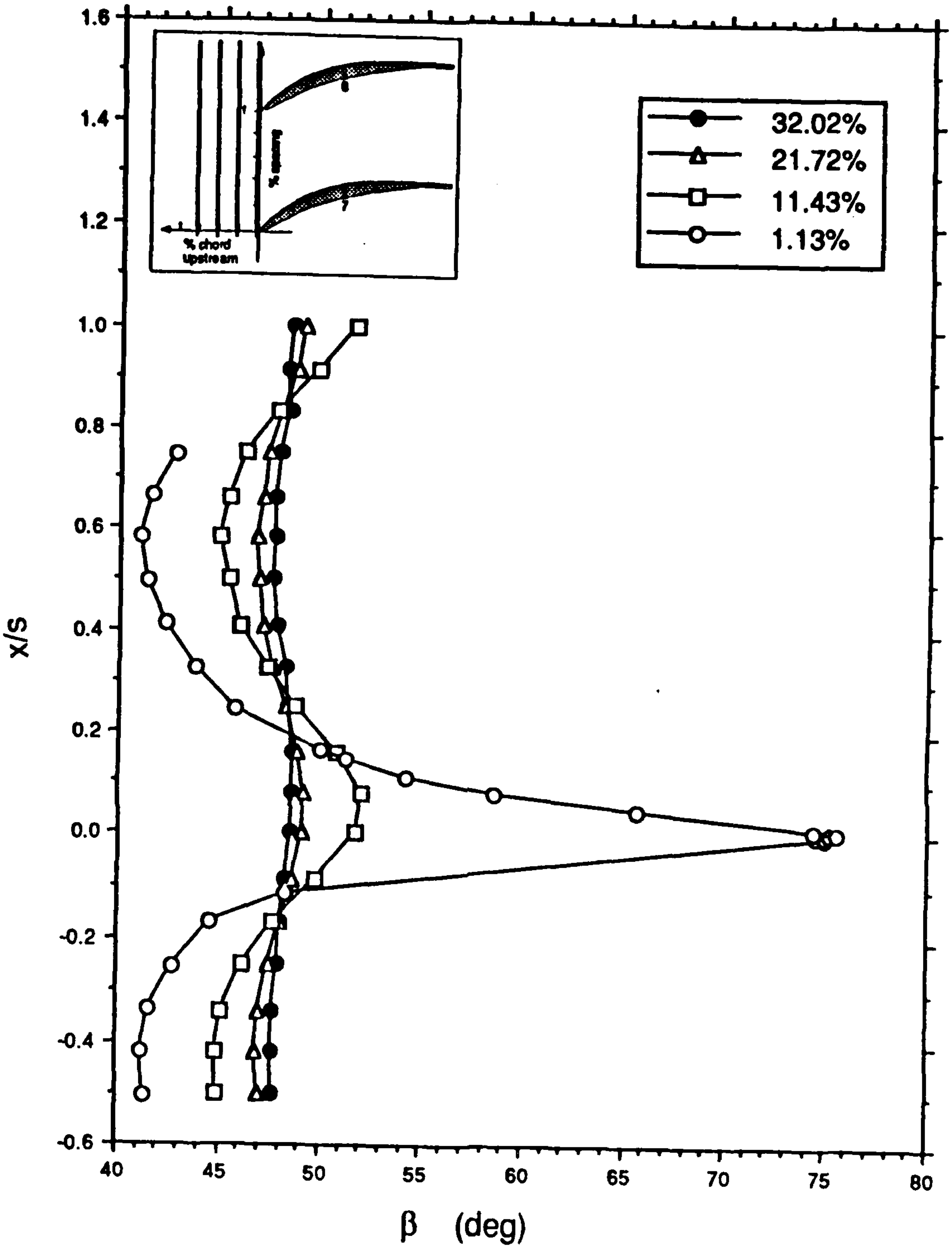

Figure 19. Inlet Flow Survey: Flow Angle Profiles

C. PASSAGE FLOW

Passage flow studies were limited to the suction surface leading and trailing edge. The frequency shifters were not installed when the measurements were taken. Yaw was set at 3.6 degrees. In documenting the results, blade-to-blade positions were normalized by the local blade passage width. The local passage width can be obtained from the blade passage geometry, which is summarized in Table XIII.

The inlet passage survey on the suction surface was measured at 0.92% axial chord downstream of the blade leading edge. The surface was approached within 3.25% of the passage width before the data rate was insufficient, without using frequency shifting. The results are given in Table XIV. Normalized velocity, turbulence intensity, and flow angle versus blade-to-blade position are shown in Figures 20-22, respectively. Velocity ratio was seen to rise smoothly to a peak of 1.4 at $x/w = 0.046$. Turbulence intensity showed a sudden change at this same location, indicating a change from the inviscid outer flow to the free shear layer region of the leading edge separation bubble. Flow angle showed a rapid decrease at the same location of peak velocity. Further resolution closer to the blade surface should be possible if frequency shifting is used.

The exit passage survey on the suction surface was conducted at 98.72% axial chord downstream of the leading edge. Only one counter was available when the measurement was taken and only the velocity component in the Y direction was recorded. The results are given in Table XV. Normalized velocity and turbulence intensity are shown in Figures 23 and 24, respectively. Because the survey was conducted normal to the local blade surface, the survey also served as a boundary layer survey for the trailing edge station. Peak velocity ratio was seen to be approximately 0.85 in the main passage area. This was about 5% larger than the

TABLE XIII. BLADE PASSAGE GEOMETRY AND SURFACE SLOPE VALUES FOR PASSAGE AND BOUNDARY LAYER SURVEYS

	Passage Limits		Surface Slopes		For Δd = 0.02 inches			
					Suction Surface		Pressure Surface	
Y (Inches)	Suction (Inches)	Pressure (Inches)	Suction (deg)	Pressure (deg)	ΔX (Inches)	ΔY (Inches)	ΔX (Inches)	ΔY (Inches)
0.0000	0.0622	2.9381	0.00	180.00	0.0200	0.0000	-0.0200	0.0000
-0.2500	0.0687	2.9550	1.00	179.50	0.0200	0.0003	-0.0200	0.0002
-0.5000	0.0752	2.9562	1.17	178.99	0.0200	0.0004	-0.0200	0.0004
-0.7500	0.0808	2.9439	1.26	175.72	0.0200	0.0004	-0.0199	0.0015
-1.0000	0.0855	2.9209	0.98	173.92	0.0200	0.0003	-0.0199	0.0021
-1.2500	0.0890	2.8904	0.47	172.11	0.0200	0.0002	-0.0198	0.0027
-1.5000	0.0890	2.8529	-0.47	170.94	0.0200	-0.0002	-0.0198	0.0032
-1.7500	0.0840	2.8102	-1.96	169.74	0.0200	-0.0007	-0.0197	0.0036
-2.0000	0.0716	2.7639	-3.77	169.21	0.0200	-0.0013	-0.0196	0.0037
-2.2500	0.0499	2.7139	-6.28	168.36	0.0199	-0.0022	-0.0196	0.0040
-2.5000	0.0156	2.6620	-9.47	168.07	0.0197	-0.0033	-0.0196	0.0041
-2.7500	-0.0350	2.6061	-13.26	166.41	0.0195	-0.0046	-0.0194	0.0047
-3.0000	-0.1005	2.5400	-16.14	163.90	0.0192	-0.0056	-0.0192	0.0055
-3.2500	-0.1815	2.4599	-20.05	160.52	0.0188	-0.0069	-0.0189	0.0067
-3.5000	-0.2833	2.3636	-24.17	157.13	0.0182	-0.0082	-0.0184	0.0078
-3.7500	-0.4102	2.2473	-29.64	153.79	0.0174	-0.0099	-0.0179	0.0088
-4.0000	-0.5639	2.1224	-33.27	152.83	0.0167	-0.0110	-0.0178	0.0091
-4.2500	-0.7396	1.9915	-37.36	152.08	0.0159	-0.0121	-0.0177	0.0094
-4.5000	-0.9318	1.8570	-38.24	151.18	0.0157	-0.0124	-0.0175	0.0096
-4.7500	-1.1847	1.7276	-40.00	183.91	0.0153	-0.0129	-0.0200	-0.0014

TABLE XIV. PASSAGE SURVEY, SUCTION SIDE: 0.92% AXIAL CHORD DOWNSTREAM OF BLADE LEADING EDGE

Final	Passage Output			
Date	3/30/89			
Lotus File	P0330001			
Beta (deg)	48.00			
STA (inches)	0.04	from LE		
STA (% chord)	0.92%			
Patm (in Hg)	30.24			
Re_c	730459			
Normalizing:		Origin: X =	-1.1847	inches
Velocity	Vref			
Turbulence	Vref			
X station	2.9123	Passage Width (inches)		
Y station	axial chord			

Run	X (% width)	u/Vref	v/Vref	V/Vref	turb_tot (%)	Alpha (deg)	Beta (deg)
1	75.02%	0.5890	0.6605	0.8850	2.02%	48.27	41.73
2	66.43%	0.6062	0.7038	0.9288	2.73%	49.26	40.74
3	57.85%	0.6301	0.7430	0.9742	3.00%	49.70	40.30
4	49.26%	0.6631	0.7773	1.0217	3.60%	49.54	40.46
5	40.68%	0.7015	0.8113	1.0725	3.93%	49.15	40.85
6	32.09%	0.7626	0.8379	1.1330	4.25%	47.69	42.31
7	23.51%	0.8385	0.8584	1.2000	4.01%	45.67	44.33
8	20.08%	0.8811	0.8563	1.2287	4.44%	44.18	45.82
9	16.64%	0.9245	0.8532	1.2581	4.66%	42.70	47.30
10	13.21%	0.9817	0.8368	1.2900	5.30%	40.45	49.55
11	9.78%	1.0584	0.8260	1.3426	6.19%	37.97	52.03
12	6.34%	1.1667	0.7077	1.3645	6.51%	31.24	58.76
13	4.63%	1.2271	0.6921	1.4088	4.54%	29.43	60.57
14	4.28%	1.2027	0.7137	1.3986	6.14%	30.69	59.31
15	3.94%	1.1422	0.7105	1.3452	7.42%	31.88	58.12
16	3.60%	1.0933	0.6997	1.2980	8.95%	32.62	57.38
17	3.25%	1.0099	0.7030	1.2305	11.43%	34.84	55.16

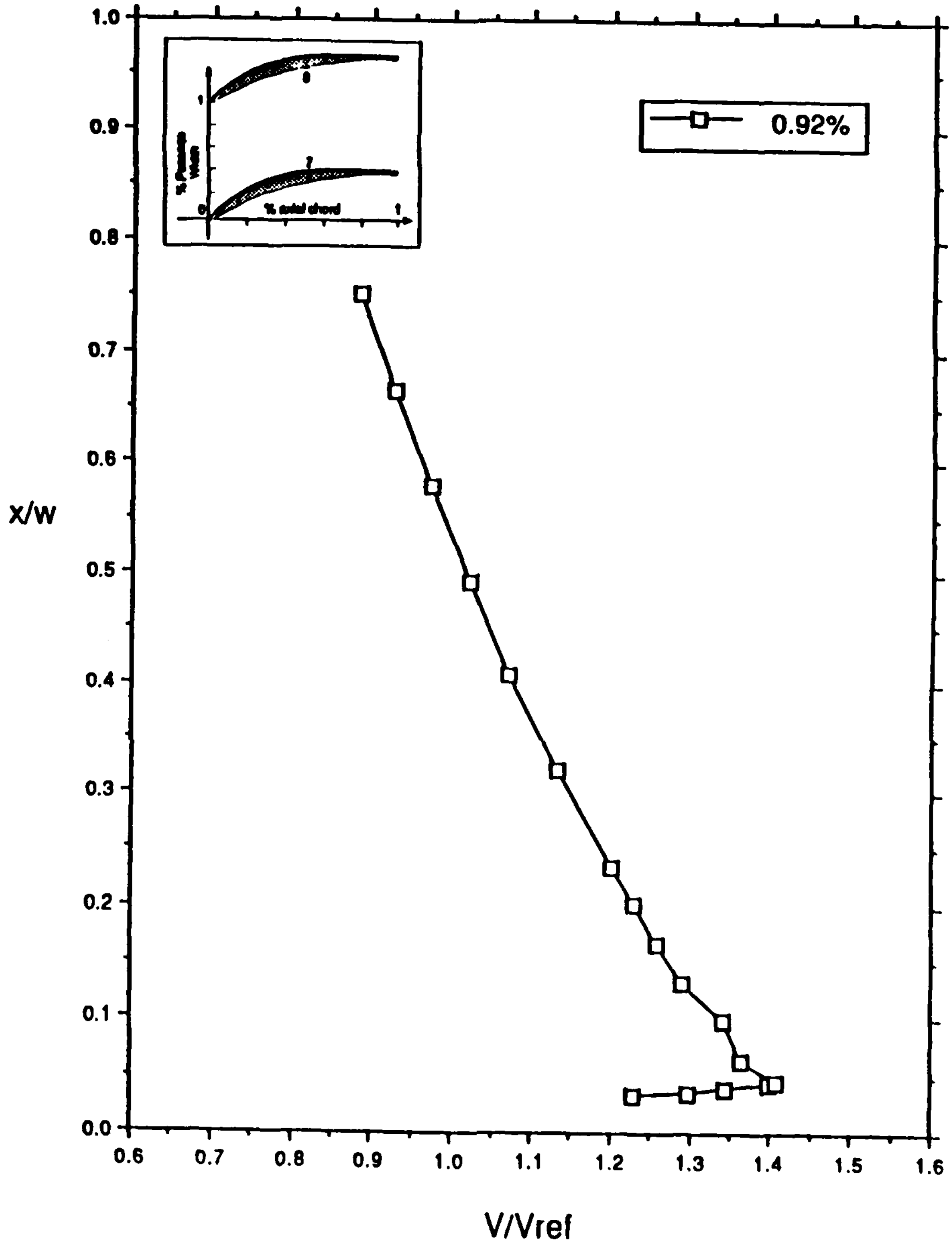

Figure 20. Passage Flow Survey: Velocity Profile, 0.92% Axial Chord

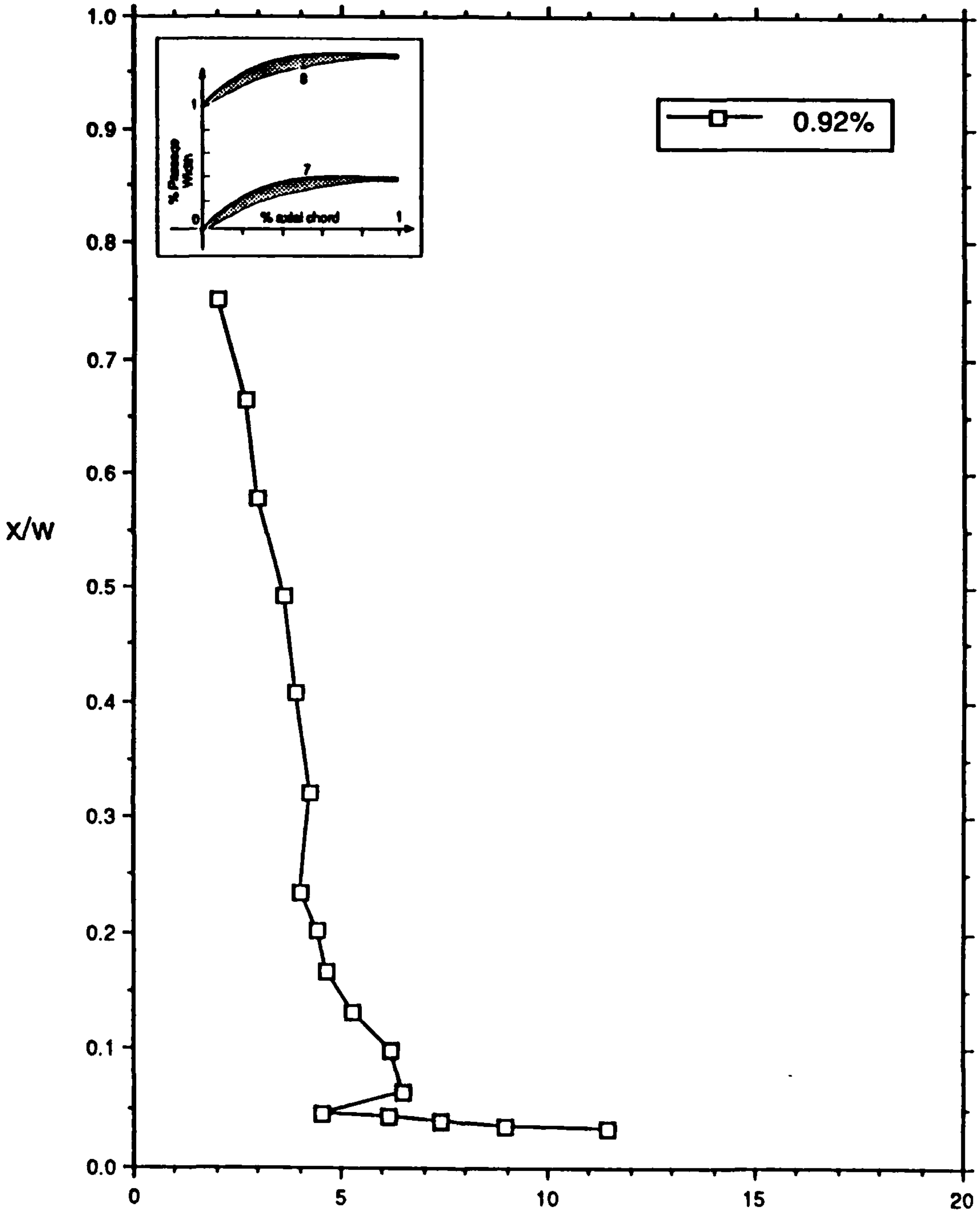

Figure 21. Passage Flow Survey: Turbulence Intensity Profile, 0.92% Axial Chord

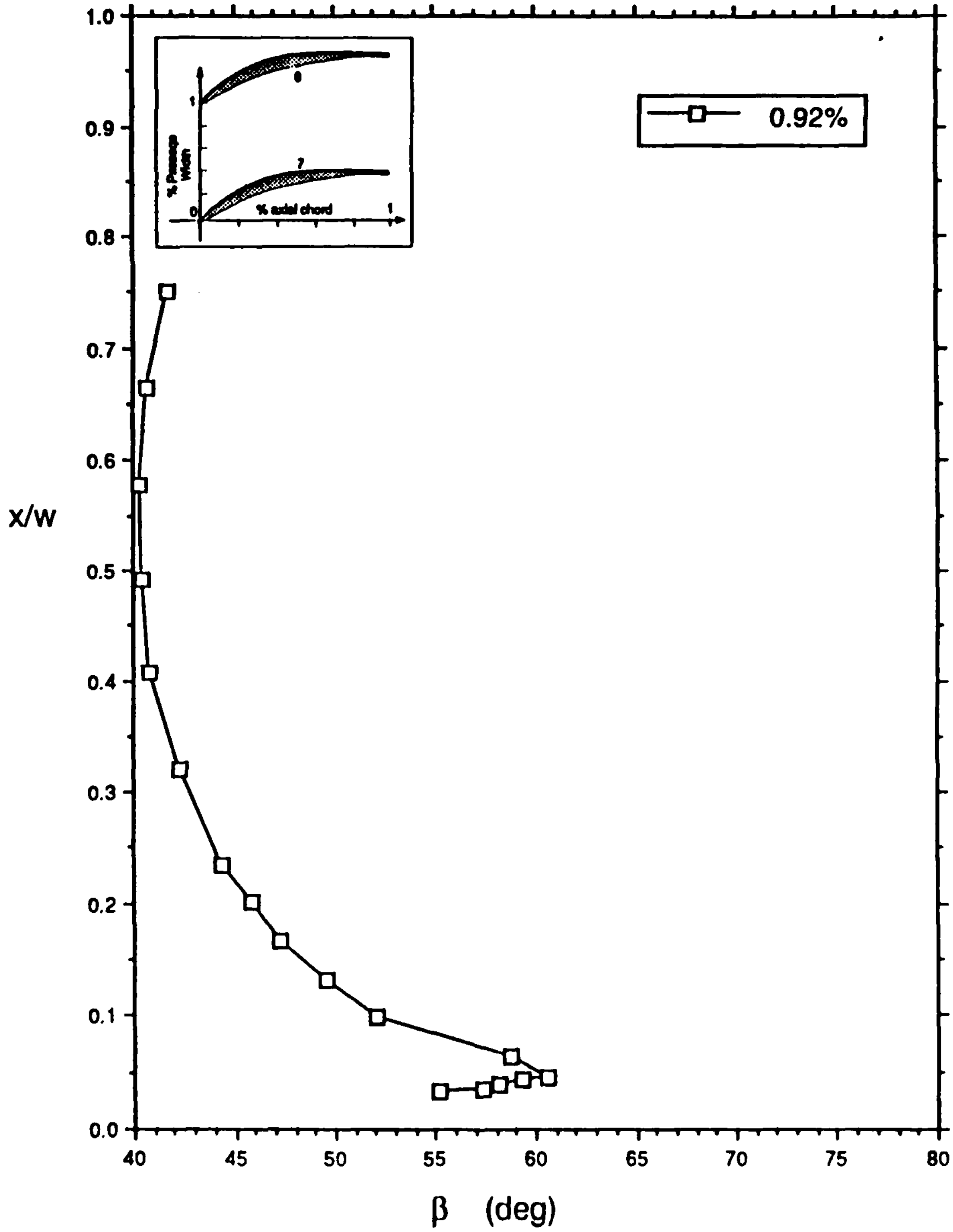

Figure 22. Passage Flow Survey: Flow Angle Profile, 0.92% Axial Chord

TABLE XV. PASSAGE SURVEY, SUCTION SIDE: 98.72% AXIAL CHORD DOWNSTREAM OF BLADE LEADING EDGE

Final	Passage Output		
Date	4/21/89		NOTES:
Lotus File	P0421001		single counter
Beta (deg)	48.00		blade passage 6 to 7
STA (inches)	4.79 from LE		
STA (% chord)	98.72%		
Patm (in Hg)	30.00		
Re_c	726219		
Normalizing:		Origin: X = -2.938	inches
Velocity	Vref		
Turbulence	Vref		
X station	2.8760	Passage Width (inches)	
Y station	axial chord		

Run	X (% width)	u/Vref	v/Vref	V/Vref	turb_tot (%)	Alpha (deg)	Beta (deg)
1	67.39%	0.0000	0.8333	0.8333	1.97%	0.00	90.00
2	63.91%	0.0000	0.8342	0.8342	1.98%	0.00	90.00
3	60.43%	0.0000	0.8350	0.8350	1.89%	0.00	90.00
4	56.95%	0.0000	0.8374	0.8374	1.95%	0.00	90.00
5	53.48%	0.0000	0.8407	0.8407	1.90%	0.00	90.00
6	50.00%	0.0000	0.8429	0.8429	1.93%	0.00	90.00
7	46.52%	0.0000	0.8450	0.8450	2.16%	0.00	90.00
8	43.05%	0.0000	0.8482	0.8482	2.14%	0.00	90.00
9	39.57%	0.0000	0.8505	0.8505	2.11%	0.00	90.00
10	36.09%	0.0000	0.8508	0.8508	2.50%	0.00	90.00
11	32.61%	0.0000	0.8512	0.8512	2.88%	0.00	90.00
12	29.14%	0.0000	0.8510	0.8510	3.38%	0.00	90.00
13	25.66%	0.0000	0.8348	0.8348	5.24%	0.00	90.00
14	23.92%	0.0000	0.7583	0.7583	8.85%	0.00	90.00
15	22.18%	0.0000	0.7321	0.7321	9.02%	0.00	90.00
16	20.45%	0.0000	0.6763	0.6763	11.87%	0.00	90.00
17	18.71%	0.0000	0.6316	0.6316	11.74%	0.00	90.00
18	16.97%	0.0000	0.6056	0.6056	12.67%	0.00	90.00
19	15.23%	0.0000	0.5529	0.5529	11.82%	0.00	90.00
20	13.49%	0.0000	0.5227	0.5227	10.65%	0.00	90.00
21	11.75%	0.0000	0.4918	0.4918	9.59%	0.00	90.00
22	10.01%	0.0000	0.4579	0.4579	8.72%	0.00	90.00
23	8.28%	0.0000	0.4165	0.4165	8.08%	0.00	90.00
24	6.54%	0.0000	0.3997	0.3997	7.44%	0.00	90.00
25	4.80%	0.0000	0.3750	0.3750	7.36%	0.00	90.00
26	3.06%	0.0000	0.2448	0.2448	7.11%	0.00	90.00
27	2.02%	0.0000	0.2294	0.2294	6.35%	0.00	90.00
28	1.67%	0.0000	0.2228	0.2228	5.89%	0.00	90.00

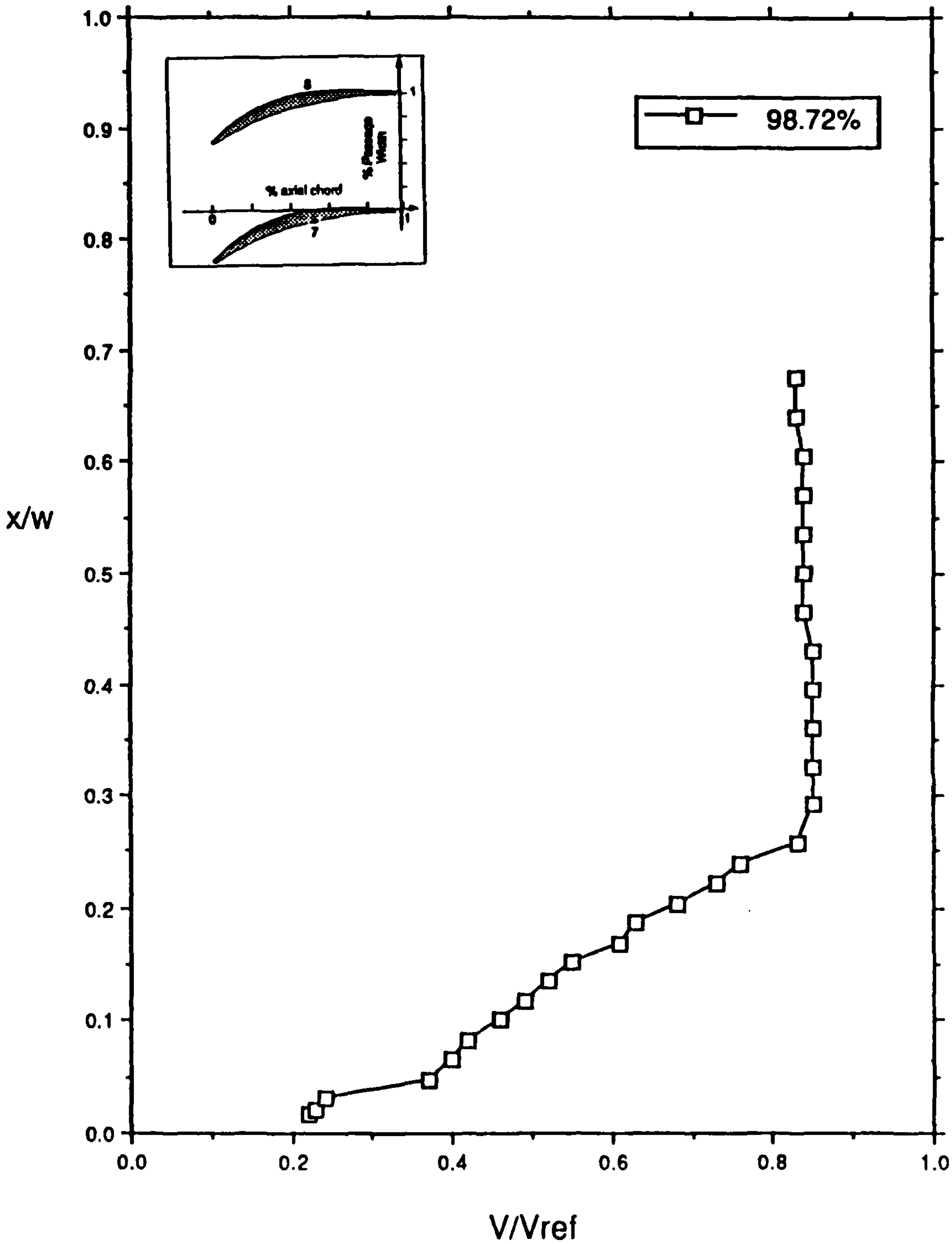

Figure 23. Passage Flow Survey: Velocity Profile, 98.72% Axial Chord

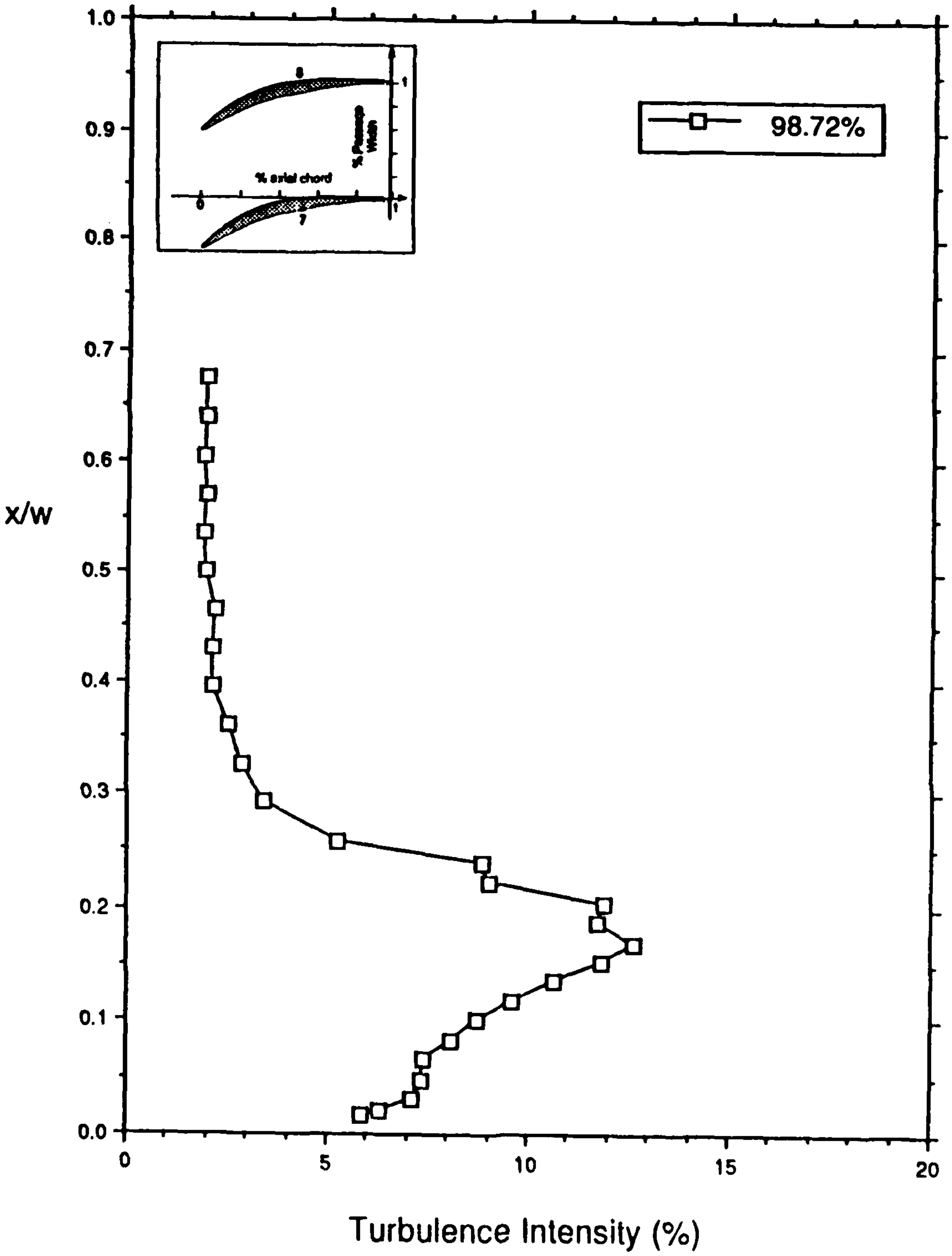

Figure 24. Passage Flow Survey: Turbulence Intensity Profile, 98.72% Axial Chord

results obtained by Elazar [Ref. 9] at $\beta = 46$ degrees, reversing the trend of a decreasing peak velocity ratio as inlet angle was increased. Additionally, the boundary layer thickness had increased significantly from about 20% to near 30% passage width. Turbulence intensity was seen to rise smoothly through the boundary layer, peaking at 13% near x/w = 0.18. The large increase in boundary layer thickness appeared to cause an increase of the outer (inviscid) passage flow when compared to lower inlet flow angles.

D. NEAR WAKE FLOW

Wake surveys were conducted at two locations downstream of the blade trailing edge. Frequency shifting was used to record the reversed flow, to prevent velocity biasing, and to increase the data rate of the horizontal (X) component. The surveys were conducted across two blade wakes to check for uniformity. The survey results for 9.02% axial chord and 19.31% axial chord downstream of the trailing edge are given in Tables XVI and XVII, respectively.

Velocity ratio is shown plotted in Figure 25. Individual horizontal and vertical velocity components are shown in Figure 26. Outside the wake, V/V_{ref} was seen to decrease to 0.83 at 9.02% of axial chord and to 0.81 at 19.31% of axial chord. The minimum velocity ratio in the blade wake reached approximately 0.25 at 9.02% and increased quickly further downstream. The trends in wake development were consistent with the results given by Elazar [Ref. 9].

Turbulence intensity for the two near wake surveys are shown plotted in Figure 27. The turbulence intensity profiles in the mid-passage at 9.02% axial chord downstream averaged 2.2%,which was only slightly higher than the inlet free stream condition. The viscous mixing process is clearly seen in the figure. The sharp turbulence intensity peak in the mixing layer from the pressure surface

TABLE XVI. NEAR WAKE SURVEY: 9.02% AXIAL CHORD DOWNSTREAM OF BLADE TRAILING EDGE

Final Wake Output

Date	6/7/89		
Lotus File	W0607001		
Beta (deg)	48.00		
STA (inches)	0.44 from TE		
STA (% chord)	9.02%		
Patm (in Hg)	30.00		
Re_c	714963		
Normalizing:			
Velocity	Vref	Origin:	Trailing Edge Blade 7
Turbulence	Vref		
X station	spacing		
Y station	axial chord		

Run	X (% spacing)	u/Vref	v/Vref	V/Vref	turb_tot (%)	Alpha (deg)	Beta (deg)
1	146.67%	0.0347	0.8024	0.8031	6.17%	87.52	2.48
2	140.00%	0.0301	0.7909	0.7915	7.69%	87.82	2.18
3	133.33%	0.0228	0.7787	0.7790	9.45%	88.32	1.68
4	130.00%	0.0158	0.7525	0.7527	12.20%	88.80	1.20
5	126.66%	0.0119	0.7145	0.7146	15.22%	89.05	0.95
6	123.33%	0.0089	0.6810	0.6811	15.89%	89.25	0.75
7	120.00%	-0.0047	0.6261	0.6261	16.39%	90.43	-0.43
8	116.67%	-0.0440	0.5471	0.5489	15.83%	94.59	-4.59
9	113.34%	-0.0845	0.4529	0.4608	13.25%	100.57	-10.57
10	110.00%	-0.1145	0.3770	0.3940	10.68%	106.90	-16.90
11	108.33%	-0.1234	0.3374	0.3593	10.19%	110.09	-20.09
12	106.67%	-0.1320	0.2869	0.3158	10.29%	114.71	-24.71
13	105.00%	-0.1366	0.2484	0.2835	9.78%	118.80	-28.80
49	103.33%	-0.1492	0.1954	0.2458	8.58%	127.36	-37.36
50	101.67%	-0.1453	0.1839	0.2344	9.05%	128.31	-38.31
16	100.00%	-0.0993	0.2877	0.3043	10.46%	109.04	-19.04
17	98.33%	0.0074	0.5778	0.5779	13.76%	89.27	0.73
18	96.66%	0.0636	0.7781	0.7807	5.11%	85.33	4.67
19	95.00%	0.0514	0.8219	0.8235	2.95%	86.42	3.58
20	93.33%	0.0490	0.8255	0.8269	2.53%	86.60	3.40
21	90.00%	0.0459	0.8249	0.8262	2.20%	86.82	3.18
22	86.67%	0.0433	0.8230	0.8242	2.07%	86.99	3.01
23	83.33%	0.0444	0.8195	0.8207	2.14%	86.90	3.10
24	80.00%	0.0428	0.8190	0.8201	2.16%	87.01	2.99
25	73.33%	0.0406	0.8158	0.8168	2.19%	87.15	2.85
26	66.67%	0.0420	0.8143	0.8153	2.07%	87.05	2.95
27	60.00%	0.0408	0.8145	0.8155	2.27%	87.13	2.87
28	53.33%	0.0413	0.8118	0.8129	2.54%	87.09	2.91
29	46.67%	0.0372	0.8084	0.8093	3.62%	87.37	2.63
30	40.00%	0.0315	0.7967	0.7973	6.22%	87.73	2.27
31	33.33%	0.0266	0.7810	0.7814	7.76%	88.05	1.95
32	30.00%	0.0251	0.7652	0.7656	9.64%	88.12	1.88
33	26.67%	0.0176	0.7318	0.7321	12.21%	88.62	1.38
34	23.33%	0.0090	0.6987	0.6987	13.93%	89.26	0.74
35	20.00%	-0.0176	0.6197	0.6199	15.69%	91.63	-1.63
36	16.67%	-0.0505	0.5278	0.5302	15.47%	95.47	-5.47
37	13.33%	-0.1026	0.4269	0.4390	12.94%	103.51	-13.51
38	10.00%	-0.1261	0.3403	0.3629	11.66%	110.33	-20.33
39	8.34%	-0.1311	0.3064	0.3333	11.09%	113.16	-23.16
40	6.67%	-0.1370	0.2611	0.2949	10.33%	117.69	-27.69
41	5.00%	-0.1414	0.2268	0.2672	10.03%	121.94	-31.94
42	3.33%	-0.1517	0.1869	0.2407	9.18%	129.06	-39.06
43	1.67%	-0.1412	0.1884	0.2355	8.66%	126.86	-36.86
44	0.00%	-0.0847	0.3622	0.3719	11.57%	103.17	-13.17
45	-1.67%	0.0445	0.6819	0.6834	10.61%	86.26	3.74
46	-3.33%	0.0571	0.7974	0.7995	3.51%	85.90	4.10
47	-5.00%	0.0472	0.8202	0.8216	2.48%	86.71	3.29
48	-6.67%	0.0446	0.8207	0.8219	2.09%	86.89	3.11

TABLE XVII. NEAR WAKE SURVEY: 19.31% AXIAL CHORD DOWNSTREAM OF BLADE TRAILING EDGE

Final	Wake Output		
Date	6/7/89		
Lotus File	W0607002		
Beta (deg)	48.00		
STA (inches)	0.94 from TE		
STA (% chord)	19.31%		
Patm (in Hg)	29.99		
Re_c	726576		
Normalizing:			
Velocity	Vref	Origin:	Trailing Edge Blade 7
Turbulence	Vref		
X station	spacing		
Y station	axial chord		

Run	X (% spacing)	u/Vref	v/Vref	V/Vref	turb_tot (%)	Alpha (deg)	Beta (deg)
1	146.67%	0.0316	0.7791	0.7797	8.15%	87.68	2.32
2	140.00%	0.0242	0.7615	0.7618	10.17%	88.18	1.82
3	133.33%	0.0155	0.7382	0.7384	12.08%	88.80	1.20
4	130.00%	0.0130	0.7189	0.7190	13.31%	88.96	1.04
5	126.66%	0.0136	0.6960	0.6962	13.93%	88.88	1.12
6	123.34%	0.0092	0.6614	0.6615	15.16%	89.21	0.79
7	120.00%	-0.0117	0.6081	0.6083	15.06%	91.10	-1.10
8	116.66%	-0.0435	0.5273	0.5291	15.20%	94.71	-4.71
9	113.33%	-0.0880	0.4354	0.4442	13.45%	101.42	-11.42
10	110.00%	-0.1115	0.3541	0.3713	11.38%	107.47	-17.47
11	108.34%	-0.1185	0.3250	0.3460	10.19%	110.03	-20.03
12	106.67%	-0.1100	0.3027	0.3221	9.65%	109.96	-19.96
13	105.00%	-0.1059	0.2890	0.3078	9.58%	110.13	-20.13
14	103.33%	-0.1000	0.2962	0.3127	9.16%	108.66	-18.66
15	101.67%	-0.0784	0.3555	0.3641	11.11%	102.44	-12.44
16	100.00%	-0.0346	0.4785	0.4798	13.10%	94.14	-4.14
17	98.34%	0.0475	0.6453	0.6471	12.38%	85.79	4.21
18	96.67%	0.0720	0.7421	0.7456	8.10%	84.46	5.54
19	95.00%	0.0723	0.7851	0.7884	4.75%	84.74	5.26
20	93.33%	0.0602	0.7987	0.8010	3.72%	85.69	4.31
21	90.00%	0.0518	0.8048	0.8064	3.13%	86.32	3.68
22	86.67%	0.0553	0.8078	0.8097	3.07%	86.08	3.92
23	83.33%	0.0459	0.8097	0.8110	2.36%	86.76	3.24
24	80.00%	0.0507	0.8075	0.8091	2.63%	86.40	3.60
25	73.33%	0.0456	0.8071	0.8084	2.48%	86.76	3.24
26	66.67%	0.0440	0.8048	0.8060	2.47%	86.87	3.13
27	60.00%	0.0403	0.8035	0.8045	2.56%	87.13	2.87
28	53.33%	0.0366	0.8000	0.8008	2.91%	87.38	2.62
29	46.67%	0.0312	0.7936	0.7942	4.29%	87.75	2.25
30	40.00%	0.0241	0.7770	0.7773	7.20%	88.23	1.77
31	33.33%	0.0190	0.7389	0.7391	11.10%	88.53	1.47
32	30.00%	0.0183	0.7276	0.7278	11.58%	88.56	1.44
33	26.67%	0.0050	0.6705	0.6705	14.92%	89.58	0.42
34	23.33%	-0.0048	0.6245	0.6245	16.70%	90.44	-0.44
35	20.00%	-0.0264	0.5603	0.5609	16.77%	92.70	-2.70
36	16.67%	-0.0604	0.4975	0.5012	14.90%	96.93	-6.93
37	13.34%	-0.0954	0.4121	0.4230	13.08%	103.03	-13.03
38	10.00%	-0.1157	0.3328	0.3524	10.36%	109.17	-19.17
39	8.34%	-0.1173	0.3083	0.3298	10.16%	110.83	-20.83
40	6.67%	-0.1166	0.2818	0.3050	9.46%	112.49	-22.49
41	5.00%	-0.1075	0.2681	0.2888	9.16%	111.85	-21.85
42	3.33%	-0.0961	0.3018	0.3167	9.57%	107.66	-17.66
43	1.67%	-0.0727	0.3898	0.3966	11.10%	100.57	-10.57
44	0.00%	0.0023	0.5498	0.5498	13.73%	89.76	0.24
45	-1.67%	0.0677	0.7052	0.7084	9.91%	84.52	5.48
46	-3.33%	0.0680	0.7691	0.7721	5.68%	84.95	5.05
47	-5.00%	0.0629	0.7898	0.7923	3.90%	85.44	4.56
48	-6.67%	0.0545	0.7979	0.7997	3.18%	86.09	3.91

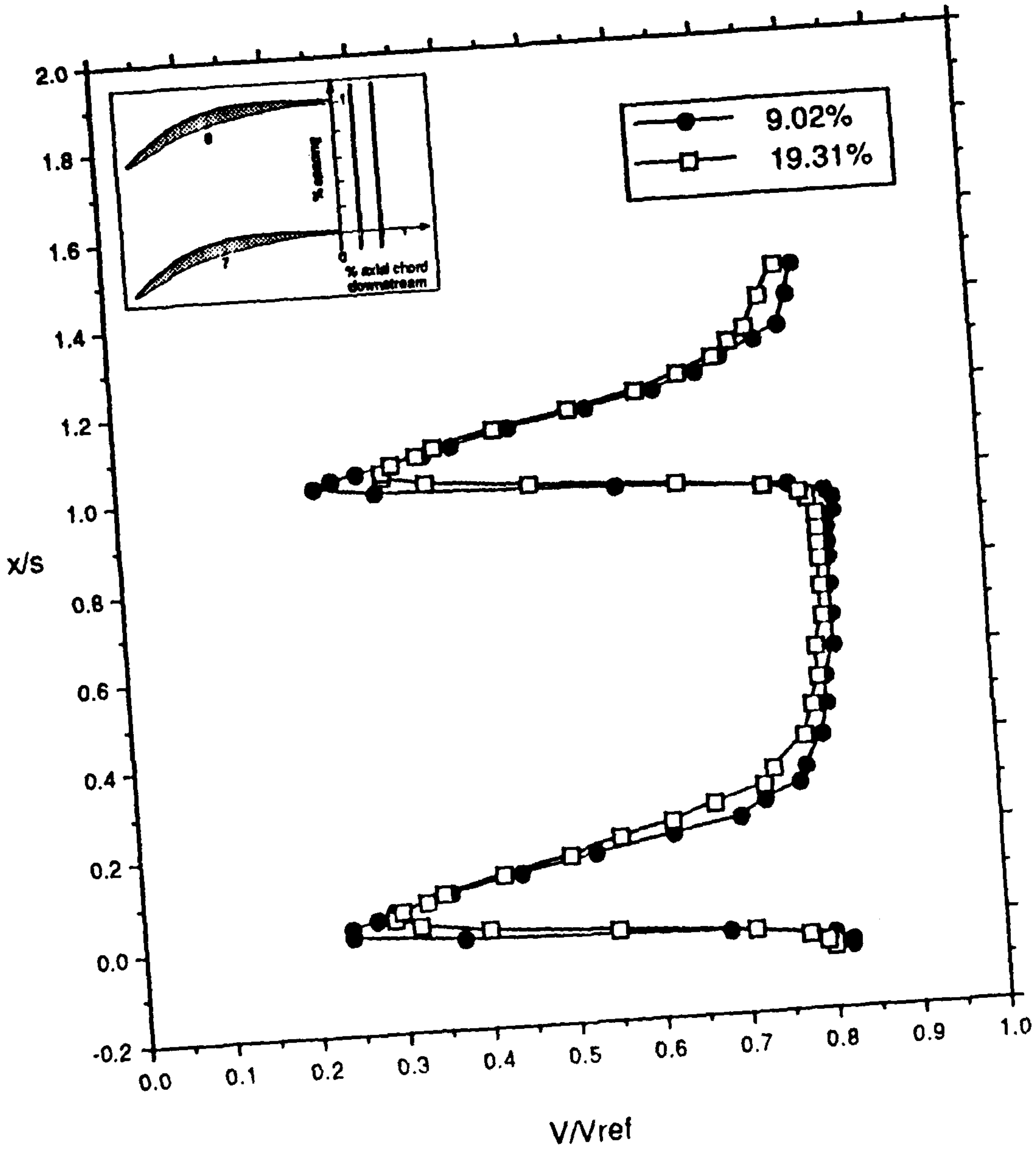

Figure 25. Wake Flow Survey: Velocity Profiles

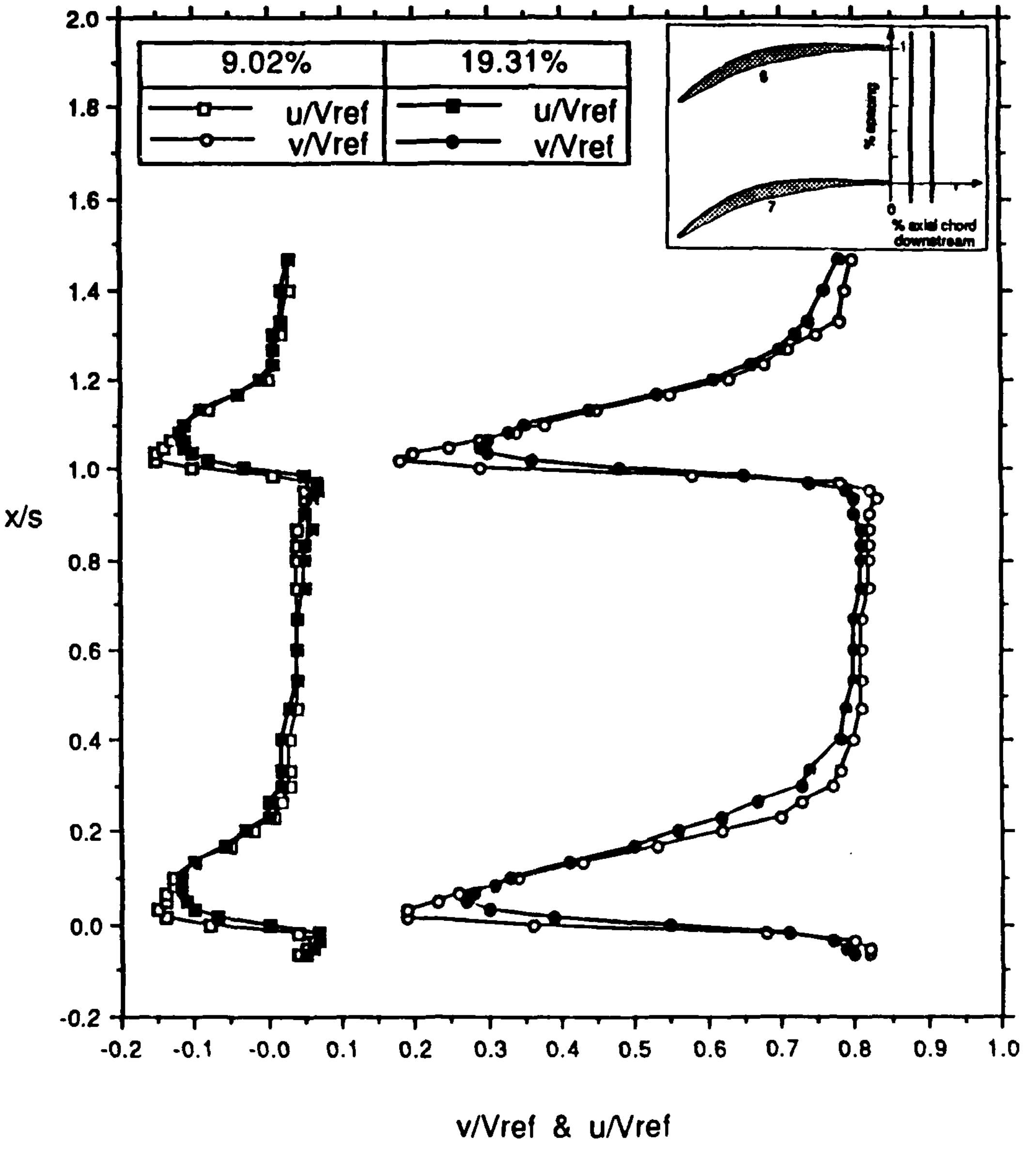

Figure 26. Wake Flow Survey: Velocity Component Profiles

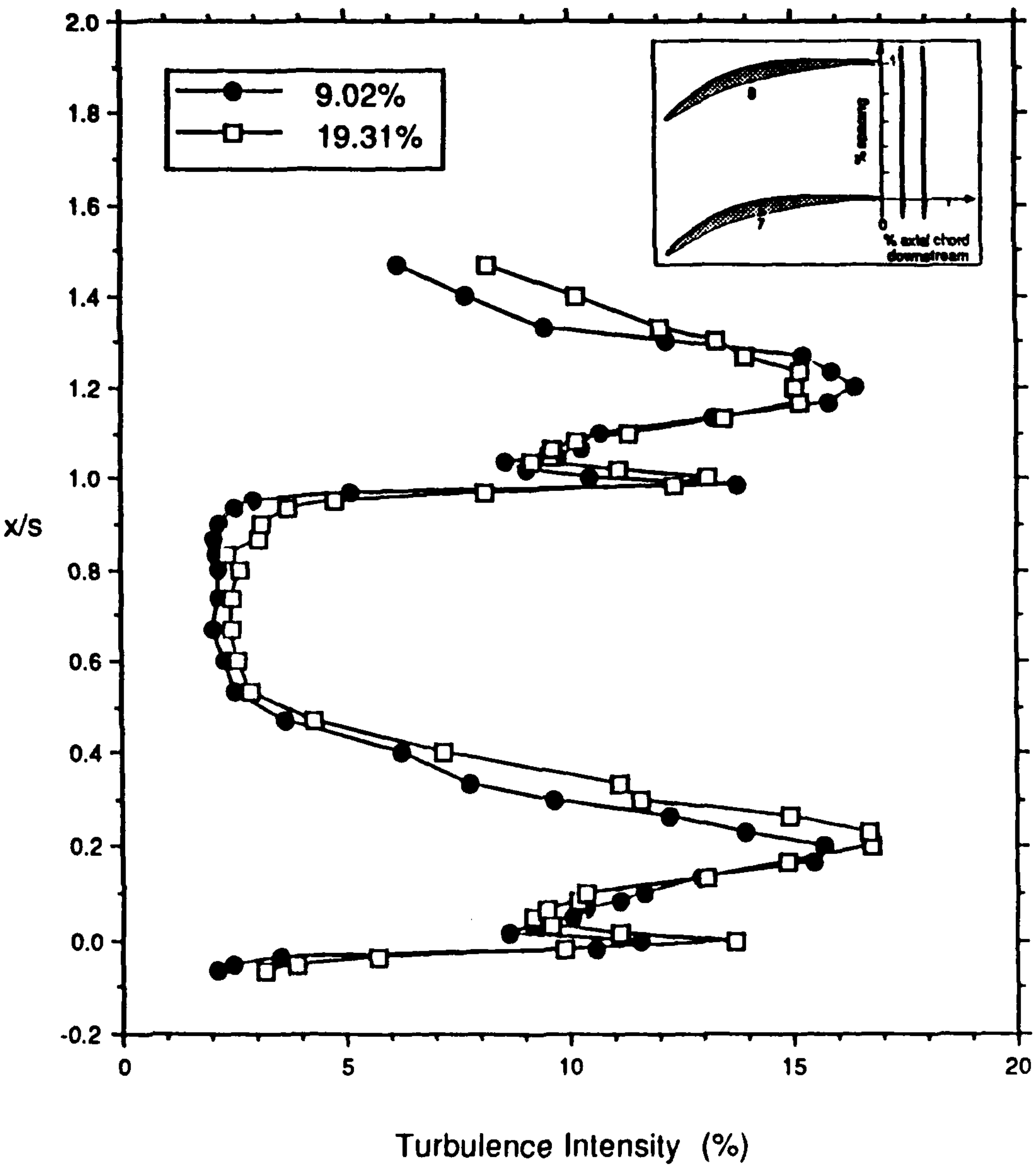

Figure 27. Wake Flow Survey: Turbulence Intensity Profiles

boundary layer and the broader peak in the mixing layer from the suction surface boundary layer, are clearly evident. The pressure side peak remained about the same as that measured by Elazar at $\beta = 46$ degrees, however, the suction side peak was significantly larger at the increased flow angle setting. The increased mixing on the suction side and the large increase in suction surface boundary layer thickness when compared to Elazar's data at $\beta = 46$ degrees, suggested that the flow had become less stable at the higher inlet flow angle and might be approaching a separated flow condition.

Flow angle profiles for the near wake surveys are shown in Figure 28. Significant deviation between the trends shown in Elazar's data at lower inlet flow angles and the results shown in the figure were noted. Elazar's data were characterized by a positive angle peak near $\beta = 8$ degrees on the pressure side and a negative peak near $\beta = -8$ degrees on the suction side of the wake in a nearly symmetric pattern. In great contrast, the data at the increased flow angle showed an extreme negative peak on the suction side. Pressure side behavior remained similar to the lower inlet flow angle settings. The downstream flow angle distribution tended to confirm a developing change in the flow behavior at the higher setting.

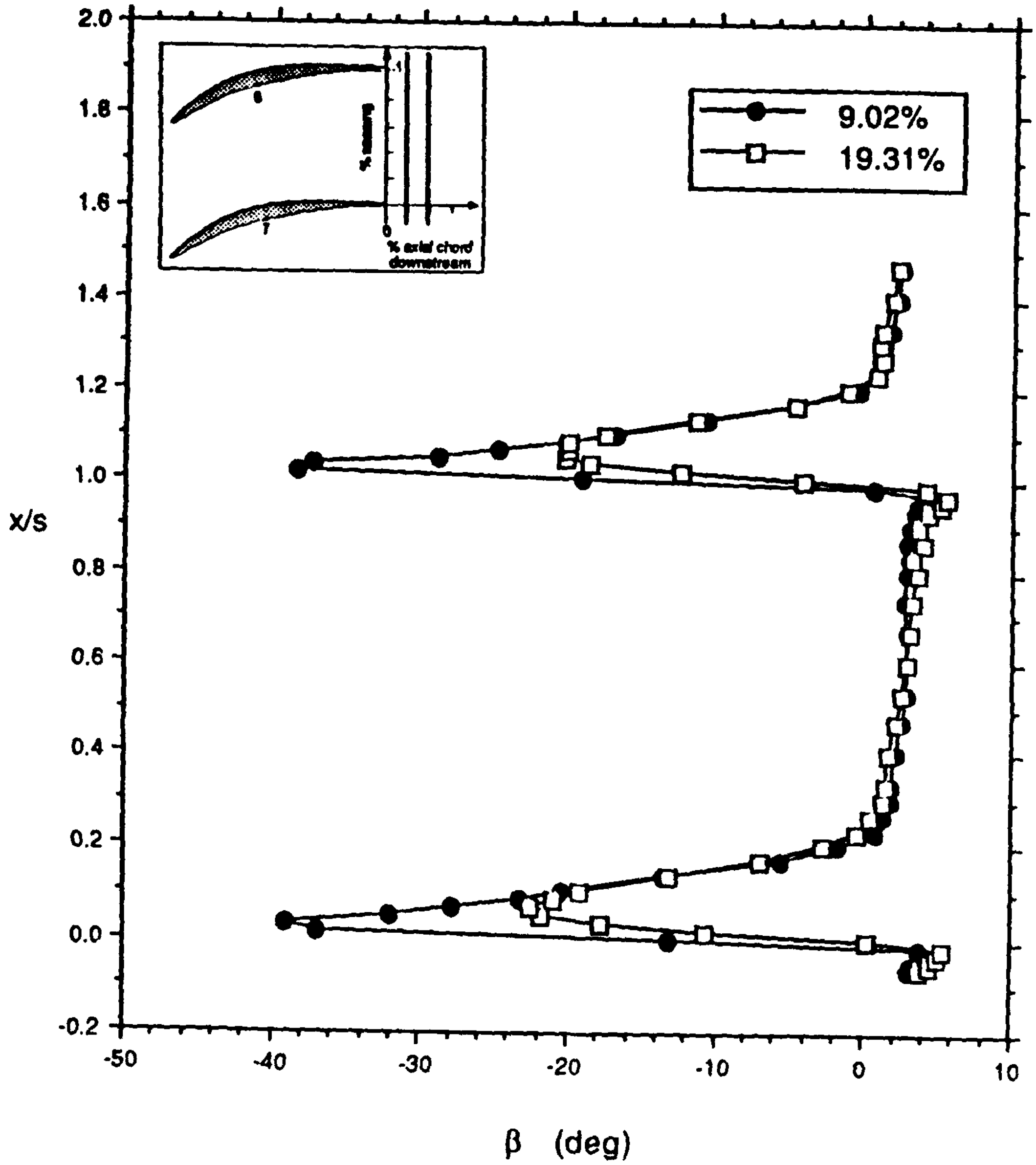

Figure 28. Wake Flow Survey: Flow Angle Profiles

IV. CONCLUSIONS AND RECOMMENDATIONS

Automation of the laser-Doppler velocimetry system for use on the Subsonic Linear Cascade Wind Tunnel was successfully demonstrated. The improved system allows for more rapid data collection and reduction, significantly reducing the time required to complete a detailed survey. In addition, a detailed operating manual covering all aspects of using the system was completed. The operating manual will permit future students to use the system productively and also allow the system to be used effectively in laboratory classes.

Although the system was significantly improved by installing the automated traverse and new data acquisition procedures, some features to improve the system are recommended. A serial data link interface between the IBM and HP computers is required. The absence of this interface in the present work required hand transfer of the pressure and temperature data to the IBM PC/AT. In addition, an anomaly in the software or hardware controlling the traverse table must yet be resolved by the vendor.

In the present application, the use of commercial software from TSI was found to severely constrain the post data reduction process and to not allow direct recording of reference measurements during the data collection. Future versions of the software have been promised by the vendor which will allow the IBM PC/AT computer to record 'extra' data, such as tunnel reference pressure and temperature, in addition to the LDV data. Such software could significantly reduce the hardware complexity of the present system by eliminating the HP 9000 computer. However, post data reduction will most likely require an in-house solution.

Measurements taken of the CD compressor cascade operating at the off-design inlet flow angle of $\beta = 48$ degrees extended the data set begun by Elazar in Reference 9. The flow was found to remain attached at the trailing edge. However, the suction side trailing edge passage survey and near wake surveys indicated changes were occurring in the basic flow characteristics from those measured by Elazar. The suction side boundary layer extended across 30% of the blade passage with higher turbulence intensities. Passage flow outside the boundary layer had a peak velocity higher than that measured by Elazar at $\beta = 46$ degrees, reversing a trend identified in his data. Wake surveys indicated that the pressure side was not changed significantly by the increase in inlet flow angle. These preliminary evaluations suggest that the flow is less stable and may therefore be close to separation on the suction surface.

It is recommended that the data set for $\beta = 48$ degrees be completed and that an increase in the flow incidence angle be attempted in order to continue the investigation to full stall.

APPENDIX A- SYSTEM OPERATING MANUAL

This appendix is intended to be used as an LDV system operating manual for measurements in the Naval Postgraduate School Subsonic Cascade Wind Tunnel located in BLDG. 213. Where applicable, a hardware/software manual is referenced and the remarks will be restricted to comments or addenda to the information in the manual.

I. LASER SAFETY

The LDV system uses a high power laser capable of causing injury to the user or observer. Consequently, the operation is strictly controlled and monitored by the school safety program. The department safety procedures are posted on the door at the entrance to the facility, and are included in this section.

System users will require a laser eye exam and also laser safety training given by the department engineer prior to being qualified to operate the laser. The department engineer will maintain records showing training and a copy of the eye exam will be kept on record. Qualified personnel will be logged into the laser operating log book when these requirements have been met. At the completion of his program on the system, the operator will have a final laser eye exam and the results will be given to the system engineer for his records.

A. DEPARTMENT SAFETY PROCEDURES

1. **NEVER LOOK DIRECTLY INTO THE LASER BEAM OR ANY STRAY BEAM. NEVER SIGHT DOWN A BEAM INTO ITS SOURCE.**
2. Do not allow reflective objects to be placed in the laser beam. Light scattered from a reflective surface can be as damaging as the original beam. Even objects such as rings, watchbands, and metal pencils can cause a hazard.
3. Beams of the laser system will not be open to the casual observer.
4. Laser power supplies are to be opened only by qualified personnel.

5. In those cases when visual access is necessary (as in system alignment), ensure the laser is turned down to minimum power, the area is clear of unnecessary personnel, and extreme caution is used to prevent exposure.

6. Warning signs will be posted at all entrances in compliance with NAVPGSCOLINST 5100.2D and ANSI Z136.

7. The warning light shall be on at all times during laser operation.

8. No laser shall be operated without sufficient safety goggles for all personnel in the laboratory. The goggles must be of the type approved for the laser in operation. The goggles shall have etched in the lens the laser types for which they are designed.

9. No laser shall be operated without a method to positively interrupt the beam.

10. No laser shall be operated which has had any of the manufacturer's safety interlocks defeated.

11. Laser beams will not be directed at an arbitrary target. If the primary target is not used, a "light dump" will be used.

12. The laser will not be operated without first notifying a staff member that the laboratory area will be occupied.

13. Each laser will have a checklist for operating the system which includes a list of protective equipment required, target preparation (if any), and start-up and shut-down procedures. These checklists must be attached to the system and be readily visible to the operators.

14. In the event of fire, the power shall be shut-off and the fire department notified. Do not attempt to extinguish the fire yourself.

15. Notify the staff engineer or laboratory manager if you have been, or suspect that you have been, injured by the laser beam.

16. All individuals planning to use the equipment will receive "hands-on" training overseen by the cognizant professor, the staff engineer, or the technician assigned to the laboratory. This training will include operational and emergency procedures as well as safety and health maintenance procedures as described in NAVPGSCHOLINST 5100.2D.

II. OPERATING CHECKLIST

This checklist is provided as a guide to operating the LDV system for taking measurements on the cascade wind tunnel. Location of specific items in BLDG 213 are labeled in Figure A-1 and are referenced by number in the checklist using brackets(i.e., [#]). Unless noted, order of shut-down is the reverse of start-up.

1. LASER

1.1. Read safety rules.[18]

1.2. Close enclosure door[18] and throw bolt lock. The laser will not start with the safety interlock broken.

1.3. Warning Light[17]– ON

1.4. Beam Attenuator[26]– Check closed

1.5. Cooling Water[1]– ON. Approx 20-25 psig

1.6. Power Plug[2]– Plug in socket. 220 VOLT

1.7. Power Supply[25]

1.7.1. Line Circuit Breakers– ON

1.7.2. Indicator Lights– Check six (6) ON

1.7.3. Key Control– ON

1.7.4. Interlock Lights– Check five (4+1) ON

1.7.5. Power On– Press

1.7.6. Power Light – Check on

1.7.7. Ready Light– Wait approx 20-30 seconds

1.7.8. Laser Start– Press

1.7.9. Power Meter Select Dial– 3 Watt

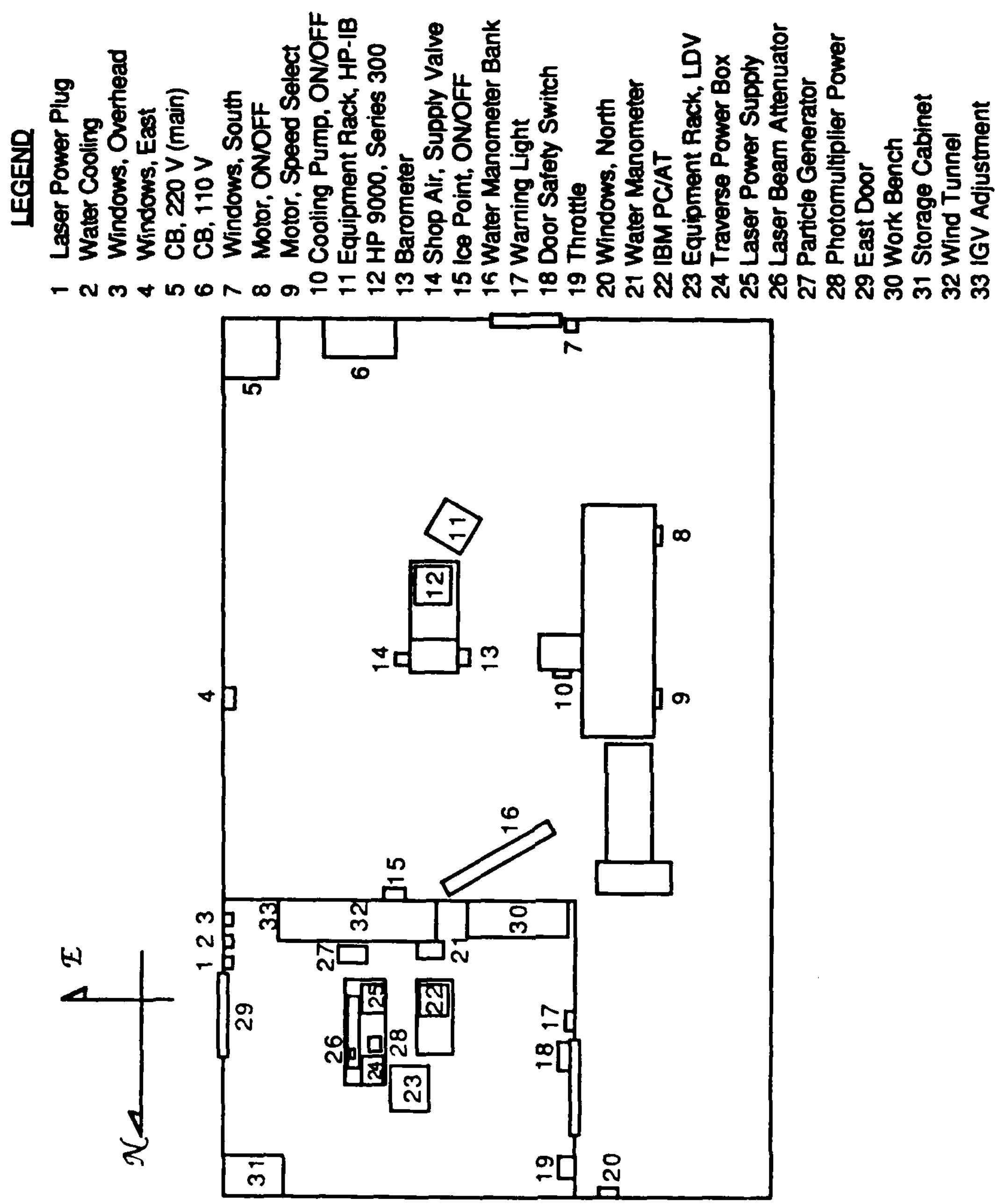

Figure A-1. Test Facility Floor Plan and Equipment Layout

1.7.10. Current Meter Select Dial– Current 50 Amp

1.7.11. Control Selector– Current

1.8. Power Adjust[25]

1.8.1. Beam Attenuator– open

1.8.2. Current Control Knob– rotate, observe Power meter for desired level. Recommended level for taking measurements is 2 Watts.

NOTE: The power meter will not function with the beam attenuator closed. If frequency shifters are installed, only two beams may be visible if the downmixers are not on.

1.9. Power-up After Interlock Break (Door opened)[25]

1.9.1. Power On– Press

1.9.2. Power Light – Check on

1.9.3. Ready Light– Wait approx 20-30 seconds

1.9.4. Laser Start– Press

2. HARDWARE

2.1. Photomultiplier(s) Power Supply[28]

2.1.1. Power Switch– ON

2.1.2. Current Control Knob– One o'clock position

2.2. Frequency Shifter Downmixer(s)[23]

2.2.1. Power Switch– ON

2.2.2. Frequency Shift Select– As desired (recommend 0 or 5 MHz)

2.2.3. Shift Direction– Into flow

2.2.4. Green– Down

2.2.5. Blue– Up

NOTE: Shift direction depends on which beam is being shifted by the Bragg Cell.

2.3. Counters[23]

2.3.1. Power Switch– ON

2.3.2. Input Conditioner

2.3.2.1. HI Limit (Low-pass Filter)– 20 or 50 MHz

2.3.2.2. Low Limit (High-pass Filter)– 1 to 5 MHz

2.3.2.3. Gain– 1

2.3.2.4. Mode Select Knob– SM/B

2.3.2.5. Cycle/Burst Rotary Switch– 3 (2^3)

2.3.2.6. Amplitude Limit– OFF

2.3.3. Timer

2.3.3.1. Comparison %– 7

2.3.3.2. Manual/Auto Switch– AUTO

2.3.4. Computer Interface

2.3.4.1. Select Switch– Coincidence

2.3.4.2. $\Delta\tau$ Interval– 5 (2^5 μs/step)

2.3.4.3. Coincident Window– x10

2.4. Oscilloscope[23]

2.4.1. Power– ON

2.4.2. Vertical Mode– ALT (Dual Trace)

2.4.3. Trigger– Slope, channel 1 or 2

2.4.4. Vertical Scale- 50 mV/DIV

2.4.5. Horizontal Scale- 0 1 to 0.5 ms/DIV

3. TRAVERSE

3.1. Power Control Box[24]

3.1.1. Power Switch: ON

3.1.2. Computer/Hand Control Switch- Computer(light in switch on)

3.2. Sony Position Encoder[23]

NOTE: The Sony encoder should be left power on. If ERROR is shown on the display press the Reset button, Axis Select and the Memory button for each axis.

To avoid loss of reference position, always position traverse to a known reference point when finished.

If the reference is lost, the template must be used to re-position the traverse.

4. IBM COMPUTER[22]

4.1. Video Display- ON

4.2. Printer- ON

4.3. CPU- ON

NOTE: The FIND software will not run with a resident program like XTREE in memory. XTREE may be used for other functions such as file management and running other programs. If XTREE is on press {F1} and {Y} to exit to DOS.

4.4. FIND Software: (from DOS only)

4.4.1. Change Directory: *Type* `CD \FIND`↵

4.4.2. Run Program: *Type* **FIND↵**

4.4.3. Menus: Check for proper settings

5. HP COMPUTER

5.1. HP-IB Bus[11]

5.1.1. Scanner– ON

5.1.2. Digital Voltmeter(DVM)– ON

5.1.3. System Voltmeter(SVM)– ON

5.1.4. Scanivalve Controller–ON

5.1.5. Patch Panels– ON (two)

5.1.6. Printer– ON

5.1.7. Plenum Thermocouple Ice-point[15]– ON

NOTE: Two icepoints exist in the same vicinity. Ensure the ice point connected has it's cable heading back towards the computer.

5.2. Video Terminal– ON

5.3. CPU–ON

5.4. Disk Drive– ON

NOTE: If the system does not load check that there is at least one HP-IB bus item on and press the **RESET** button (upper left corner of Keyboard).

5.5. Remote Control Software:

NOTE: HP Basic (operating system) is case sensitive, so typing **"CASCADE"** is not the same thing as typing **"cascade"**. Also, the quotes are required.

5.5.1. Change Directory: *Type* **MSI "CASCADE"↵**

5.5.2. Load the Program: *Type* **LOAD "LDVREM"↵**

NOTE: The function keys at the top of the keyboard can be used for key words such as LOAD{F5}, RUN{F3},CONT{F2}, etc.

5.5.3. Run the program: Press {F3}

5.5.4. Calibrate the Scanivalve:

5.5.4.1. Patch Cord: Connect the cord between the green/white terminals on the scanivalve control panel for the scanivalve(labelled 1) and the green/white terminals for the DVM (adjacent to SVM).

5.5.4.2. Scanivalve: Set to port 1(reference zero port)

5.5.4.3. Scanivalve Control Panel: Adjust ZERO knob until it reads zero (0).

5.5.4.4. Scanivalve: Set to port 2(calibration port)

5.5.4.5. Shop Air Valve: Adjust manometer for approx. 8-10 inches (valve on top of equipment rack. Check that the proper pressure tube is connected to the valve and manometer if the DVM does not indicate properly)

5.5.4.6. Scanivalve Control Panel: Adjust the SPAN knob until it reads the same as the water manometer (inches H2O x 10^{-4}).

5.5.4.7. Scanivalve Control Panel: Reset the scanivalve to port one (1)

5.5.5. Answer questions at the prompt:

5.5.5.1. Scanivalve Controller: Check all scanivalves set to one (1), then press CONT {F2}

5.5.5.2. File Name: Limit to 8 digits, no quotes, recommend same as IBM file name. Example:

WMMDD##

where:

first letter: W(ake), P(assage), B(oundary layer), I(nlet survey)

MM pair: Month

DD pair: Day of month

pair: Survey serial number

5.5.5.3. Barometric Pressure[13]- Enter in inches Hg

5.5.5.4. Light- Check light ON (top of equipment Rack and also light at IBM terminal). System is now ready to take data from the remote switch also located at the IBM terminal.

6. WIND TUNNEL

NOTE: The wind tunnel exhausts to the room so the windows must be open. The main blower uses water cooling and the pump must be on for the power switch to function.

Because of power requirements, the tunnel MAY NOT BE OPERATED when the compressor in BLDG 215 is running. Work out scheduling with other researchers and the technician.

6.1. Windows[3,4,7,20]- Open all windows (4 buttons)

6.2. Cooling Pump[10]- ON

6.3. Throttle[19]- Check idle position

6.4. Speed Select[9]- Check LOW

6.5. Power[8]- ON (Use log book for recording time on and off)

6.6. Speed Select[9]- Set to HIGH (Required for surveys)

6.7. Throttle[19,21]- Adjust for desired plenum pressure (Use manometer near tunnel)

Surveys: Approx. 12 to 13 inches water (Approx. 1/3 throttle)

7. PARTICLE SEEDER[27]

NOTE: To avoid excessive build-up of oil on the blades, the particle seeder should be activated only when surveys are being conducted or the system is being tested.

7.1. Shop Air Inlet Valve- UP (on)

NOTE: If no shop air, check that the main valve[14] is open and, if necessary, check for shop air on (pump in BLDG 214).

7.2. Pressure Gauge- Check for 40 psig (Exit gauge will measure zero as this reflects the amount of back pressure in the system relative to plenum pressure)

7.3. Oil Flow- Adjust tube wheel knob for minimum flow. The bottle will bubble and a fog-like mist will fill the bottle. If you can see the scattered laser light in the tunnel you have enough particles entering the flow.

7.4. Nozzle Location- Turn to direct nozzle to blade passage desired

Blades 6-7: 345-350 deg

Blades 7-8: 340-350 deg

8. TAKE DATA

NOTE: All data collection and system adjustments can be made from the desk area with the exception of tunnel speed adjustment and seeder nozzle control.

8.1. Enclosure Door– Close and bolt

8.2. Laser– Restart (Check power level at 2 Watts, the system tends to change power level when the tunnel is turned on).

8.3. Counters/Frequency Shifters– Adjust gain and filters for sufficient data rate.

8.4. Data Rate– Typically the rate should be between 40-100 readings per second.

8.5. Oscilloscope– Observe signal, ensuring that the counters are not recording noise (Excessive data rate above 200 usually indicates noise is being recorded).

8.6. FIND Software

8.6.1. Main Menu– Select Traverse Table Control Program{T}

8.6.2. Select - Automatic Traverse File

8.6.2.1. Edit- Check file for proper settings ({esc} to exit)

8.6.2.2. Return to main menu

8.6.3. Main Menu– Select Data Acquisition Program {A}

8.6.4. Data Acquisition Menu

8.6.4.1. Automatic Traverse Parameters{T}– Check Traverse Table is activated

8.6.4.2. Data File Management{F}– Check for:

Correct Family Name

Experimental File Number– Set to one(1)

Positions per Analysis– Set to one(1)

Data File Path– C:\LDVDATA

8.6.4.3. Processor Setting{P}– Check for:

Number– 2

Number K-data Points– 1 (or as desired)

TBD– ON (hardware setting internally in counter)

DMA Time-out– 60 sec

Acquisition Mode– Coincident

Processor Type– 1990

Counter Mode– SM/B (address 0 & 1)

NOTE: All other data is for documentation only.

8.6.4.4. Optics{O}– Check for:

Frequency Shift– Set same as downmixer (shifting into flow direction is entered as a positive number)

Focal Length– 762 mm

Half -Angle– 3.1 deg

Wavelength– Set to proper beam color

BLUE = 488.0

GREEN = 514.5

NOTE: If any changes are made to cause the fringe spacing to be changed (wavelength, Half-angle), the calculate function should be used (use half-angle method).

8.6.4.5. Real Time Histogram{R}: Take data from this menu

Edit– Axes control can be adjusted

Zoom– Look at an individual counter

Stats– Get real-time statistics (reflects units of horizontal axis{velocity or frequency})

Menu– Full access to all the above menu items except traverse control

{F2} & Remote Switch– Takes data

NOTE: If traverse table is active, the program will automatically position the table, take data, and then return to the real time display.

The remote switch should be momentarily pressed until the light is observed to go out, then released. The system will be ready to take another reading when the light comes back on.

8.6.4.6. Data Collection– Repeat for each position.

NOTE: Adjustments may be necessary on counter gain, particle seeder position, counter filters, laser power, and frequency shifting.

8.6.5. Data Collection Finished:

8.6.5.1. Menu– Return to main menu (<esc>, {M});

Press QUIT {Q}

NOTE: Selecting QUIT from the main menu will

transfer to AUXMENU, where data reduction can be selected.

8.6.5.2. Data Reduction– Continued after shut down

9. SHUTDOWN

9.1. Particle Seeder[27]– Off

9.2. Laser

9.2.1. Beam Attenuator[26]– Closed

9.3. Tunnel

9.3.1. Throttle[19]– Idle

9.3.2. Speed Select[9]– LOW

9.3.3. Power[8]– OFF (log book)

9.4. If finished taking data:

9.4.1. Hardware– All off

9.4.2. Laser– Off

9.4.3. Tunnel–Pump off

9.4.4. Windows– Close

9.5. Computers– Leave on for data reduction

10. DATA REDUCTION

10.1. HP 9000

10.1.1. LDVREM

10.1.1.1. End Data Collection– {F1}

10.2. HP Operating System

10.2.1. Remove program from memory– Select PURGE {F4}

10.2.2. Load "PRINTDAT"– *Type* `LOAD "PRINTDAT"`↵

10.2.3. Run Program– Select RUN {F3}

NOTE: PRINTDAT will print to the printer and screen the reduced data from the run. PRINTRAW will print out the raw values recorded.

Printer must be on.

10.3. IBM

10.3.1. AUXMENU

10.3.1.1. Data Reduction(Raw to Stats)- Select{D}

10.3.2. REDRAW

10.3.2.1. Answer questions when prompted.

10.3.2.2. Processing all data in order is recommended.

10.3.2.3. Refinement- For 1K data points, Chauvenet's Criterion gives 3.5 as a good value for refinement.[Ref. 12]

10.3.2.4. Quit- When done

10.3.3. AUXMENU

10.3.3.1. Quit- When done (exits to DOS)

10.3.4. DOS

10.3.4.1. *Type* **XTREE**↵

10.3.4.2. Select **LOTUS123** Directory

10.3.4.3. *Type* **X**↵

10.3.4.4. *Type* **123**↵

10.3.5. LOTUS 123

NOTE: To activate the menus, press the backslash key "/"(this is the key with the question mark).

Use the cursor keys and return (↵)or type the first letter of a

menu name to select.

To extend or change a range, press the escape key [esc] and the period key [.].

10.3.5.1. Open a Worksheet:

Menu Select– /, `File, Retrieve`

Select the appropriate worksheet

Inlet Reference Survey:

FREESTWS.WK1

Inlet Survey:

INLETWS.WK1

Passage Survey:

PASSWS.WK1

Boundary Layer Survey:

BOUND.WS1

Wake Survey:

WAKEWS.WK1

10.3.5.2. Header– Fill in information for survey

10.3.5.3. Import Data from LDV:

Position Cursor– Cell [A21]

Menu Select– /, `Import, Number`

Type **`*.DAT`**↵

Select File name with cursor then ↵

NOTE: Data from the LDV Reduced data file will fill the worksheet from the cursor position.

10.3.5.4. Enter Data from HP(Tunnel conditions):

Position Cursor– Cell [L20]

Enter– Barometric Pressure

Position Cursor– Cell [L21]

Enter– Each Plenum Pressure in column [L]

Enter– Each Plenum Temperature in column [M]

Enter– Run numbers in column [K]

10.3.5.5. Extend Formulas from row [21] to all rows with data:

Position Cursor– Cell [N21]

Menu Select– /, Copy

Extend Copy From Range to Cell [AE21]↵

Copy To Prompt– Position Cursor [N22]

Type: [.]

Position Cursor– [N##]↵

where: ## means extend down the column to include all rows with data input.

10.3.5.6. Calculate– {F9}

10.3.5.7. Print Results:

Menu Select – /, Print, Printer Range

Cursor– position and select range to be printed (recommend last "page" of final data)

Menu Select – Go

10.3.5.8. Save File:

Menu Select – /, File, Save, {esc},{esc}

Rename– File name desired(Do not save without changing name as this will replace the worksheet).

10.3.5.9. Quit:

Menu Select – /, Quit, Yes

10.3.5.10. Reactivate XTREE– Press ↵

III. LASER

Reference:

Lexel Corporation, *Model 95 Ion Laser Manual*, 1983.

Operation of the laser is generally hands-off with only minor adjustments of the mirrors if peak power is diminished. Movement of the laser from the platform is not recommended. If the laser is moved the beam will most likely be lost and the mirrors will have to be walked. The laser should put out 4-6 Watts of peak power if properly tuned.

Power supply settings were checked according to the instructions in Operation, Initial Operation, and were found correctly configured.

Page numbering is non-existent in the manual so reference will be by chapter title and subtitle. A system brochure located at the front of the manual is a good reference for Lexel equipment and operational modes.

A. TUNING/WALKING MIRRORS

Information for normal tuning is located in the Operation chapter, Normal Tuning Procedure. The manual gives an adequate description of the procedure. This should be the only type of tuning required.

If the laser is drastically detuned, follow the Mirror Walking Procedure. This process requires patience but does work. Adjustments should be in very small increments. Overshooting and undershooting the best setting will most likely occur requiring smaller adjustments as the procedure progresses.

B. CLEANING LENSES

Lens cleaning is not recommended. Attempting to clean the optics will most likely result in scratched optics and a destroyed system. If cleaning is attempted, some of the equipment is located in the LDV accessory box located on the work table. Not all the equipment exists to accomplish cleaning the lenses properly.

C. ETALON

The etalon and associated circuit board was removed from the laser because the lens had become permanently fogged from previous use. The purpose of the etalon is described in the brochure located at the front of the manual. The removed parts are stored in the LDV accessory box located on the work table.

IV. OPTICS

References:

(1) TSI Incorporated, *Laser Velocimetry Systems Catalog*, 1984

(2) TSI Incorporated, *System 9100-7 Laser Doppler Velocimeter Instruction Manual*, 1984

(3) TSI Incorporated, *Model 9180 Frequency Shift System Instruction Manual*, 1984

Reference 1 provides good detailed information on system components. Information includes component features, applications, and specifications. A chapter titled Technical Data provides a concise summary of laser velocimetry techniques specific to the types of systems TSI services. Details on LDV techniques, dual beam systems, photodetector signals, noise, signal processing, data processing, and particle requirements are provided. In addition, a bibliography is provided in the back of the manual which addresses the topic of LDV.

A. TRANSMITTING OPTICS ALIGNMENT

Alignment of the LDV optics is detailed in Reference 2. The manual includes a summary description of each system component in Chapter Two. Refer to Reference 1 for a more detailed description. Chapter Four contains the alignment procedures. Annotations have been added to the margins with tool sizes and other information which needed clarification. Chapter Seven includes a summary of some of the data found in Reference 1.

Alignment of the system should not be required unless the system is disturbed or it is desired to remove the frequency shifters. Efforts should be made to avoid disturbing the optics between the laser head and the exit of the color separator. The system can then be rebuilt rather quickly starting from the color separator exit starting at paragraph 4.6.

1. Using Alignment Mask/Blocks

In paragraph 4.6.3 the alignment mask is introduced to check the position of the beams on a stenciled grid. Often, the grid does not line-up with the alignment blocks. The alignment can usually be adjusted by slightly shifting the optical components horizontally until aligned before clamping to the base.

2. Installing Frequency Shifters

Frequency shifters are installed following Reference 3. Disregard the comments on direction of fringe movement(page 6) since with the newer system this item is selected by a button on the downmixer. However, the arrow does point in the direction which will be labeled "down" on the downmixer control box. The ring is set to point away from the box-like attachment on the module.

The alignment mask is used again in the installation of the Bragg Cell (page 8). In order to have good separation of the shifted and unshifted beams, the mask should be placed at a reasonable length from the Bragg Cell exit. After the tilt adjustment is set for optimum energy in the shifted beam, the locking screw must be set or the block will slip. Care must be taken when installing the cables to avoid loosing the alignment as the locking screw does not appear to have enough bite to avoid slipping.

Observing the shifted output on the counter as described on page 9 cannot be accomplished until the complete system is built.

a. Beam Steering

The beam steering modules are installed in paragraph 4.6.6 of Reference 2. For preliminary alignment the beams should be rotated out of the path as described. When rotated back into the beam path, paragraph 4.7.9, the frequency shifted beam should be the beam travelling through the steering module. The beam steering module will allow for alignment of the two individual beams from one color but will not provide the adjustment to bring the two colors together. The fine adjust screws on the Model 9107 Mirrors will bring the two colors together.

b. Beam Stop

The beam stop should be orientated to block the beam which had frequency shifting applied(paragraph 4.7.6). The 9181-4 has adjustments for both colors on one component. Each socket screw controls only one side of the adjustment so that the stray beams on both sides of the main beam may be blocked.

3. Probe Volume Alignment

Probe volume alignment is achieved by adjustments to both the steering modules and the fine adjust screws on the Model 9107 Mirrors.

a. Fringe Projection

Since the arrangement of the system does not provide sufficient distance to observe a projected probe volume(paragraph 4.7.9), a mirror is used to deflect the projected beams to the east wall of the enclosure(parts are located in the cabinet in the northeast corner of the enclosure).

A piece of plywood (approx. 2 x 3 ft) is clamped to the lip of the tunnel wall just below the optical window. The plywood provides a platform for the Microscope Objective and the mirror. The mirror is orientated horizontally and

supported by an adjustable lift at one end and a metal bar at the other. The Microscope Objective is then hand-positioned until the projected beams cross on the wall. Adjustments can then be made to bring all four beams to the same point. The platform should be taken down when alignment is complete. Note, the projected probe volume will only show the fringe pattern if the frequency shifters are not installed.

B. RECEIVING OPTICS

Alignment of the receiving optics components is extremely important. The photomultipliers must be adjusted so that the scattered light is focused and centered on the small pinhole located on the bottom plate of the photomultiplier head. The system does not include the field stop system described in paragraphs 4.7.5 and 4.7.10.

1. Photomultipliers

Adjustment of the photomultipliers begins at paragraph 4.7.12. Adjusting the focus is not normally required after initial adjustment. Alignment of the pinhole is a two step process.

The first step requires placing a scatter plate (an alignment block works OK) at the beam crossing point. Power should be at a minimum. The photomultiplier head is removed and replaced by the alignment eyepiece. The eyepiece does not need to be installed for this adjustment since the scattered light spot is bright enough. Using the thumbscrews on the 9143 the light spot should be centered in the reticle. Observing a scattered flow to center the spot is nearly impossible because the intensity of the spot is very weak compared to the background.

The second step requires replacing the photomultiplier head and using a seeded flow under nominal test conditions. The tunnel need not be running at full speed but the flow region should provide sufficient velocity for both components(inlet to the blade row is OK). The counters and the oscilloscope will be used to optimize the final adjustment of the photomultiplier head. Make small adjustments to the 9143 thumbscrews, searching for the region where the data rate is optimized and the noise is minimized. Usually the adjustment will be within one full turn of the thumbscrew. If the spot can not be found, go back to the first step. Sometimes the scattered light can be observed using the alignment eyepiece with the eyepiece installed.

With the adjustments complete the system should now be ready to use. Care must be taken that the cables do not pull on the head and cause the alignment to be lost.

V. COUNTERS

Reference:

TSI Incorporated, *Model 1990C Counter-type Signal Processor Instruction Manual,* 1984

The counters have numerous selections and setting for processing the data, some of which are critical, others which are not so critical. The discussion that follows is only a recommendation based on experience gained so far.

A. SWITCH SETTINGS

The primary selection is the choice of mode(CONT, SM/B, TBC, TBM). Single measurement per burst mode (SM/B) has been used for all measurements taken to date. Continuous mode (CONT) has been used when trouble shooting using a signal generator.

The cycles per burst dial is used to fix the number of cycles that the counter will measure for a valid signal. A setting of 3 (2^3=8) has been used successfully. Since only 28 fringes define the probe volume, using 4 (2^4=16) may bias the results and a smaller number may not provide sufficient accuracy in the measurement. When the setting is 3, the timer automatically uses a 5/8 comparison ratio to check for signal validity(measuring the same particle). The comparison % switch located on the timer works with the comparison ratio check and has been left at the recommended value of 7%.

The low limit filter is a high-pass filter which removes the low frequency component of the signal. The primary purpose of the filter is to remove the pedestal

component of the signal. the high limit filter is a low-pass filter which removes high frequency noise from the signal. Both filters should bracket the expected signal range with sufficient bandwidth to include expected turbulence deviations. If frequency shifting is used, the downmixer has a built in low limit filter which performs the roll of removing the pedestal. Consequently, setting the low limit filter on the counter is not as important and the bandwidth can be opened up. The high limit filter can usually be left at one setting(20 or 50 MHz) without significant affect on the data rate.

The amplitude limit has not been used successfully and should be left off. The purpose of the switch is to filter out signals with large amplitudes to reduce the probability of making measurements on particles that are so large they may not be following the flow. The indicator light will flash red if the limit is exceeded. In principle this switch can be used, especially if large particles in the flow is a concern, however, there is no calibration method to confirm that this switch is actually filtering out the slower moving large particles.

Finally, the gain control is probably the most frequently adjusted switch on the counter. The gain should be adjusted so that the green indicator light is on and steady with sufficient data rate but without amplifying noise. Amplification of this setting are discussed further under section C, Data Rate Optimizing.

The timer should be left in auto with the comparison % switch set at 7. These settings never need to be changed.

On the readout module are two digital displays, output and data rate. The output display indicates the analog equivalent voltage being generated by the timer. The display could be calibrated to show velocity or frequency but this would require a fixed exponent on the timer. Fixing the exponent does not guarantee the

timer will optimize the digital resolution of the signal and should be avoided. The data rate display is necessary for monitoring the signal. The selected resolution should be set at 1 which controls the decimal point on the displayed value and also the frequency the display is updated. For a setting of 1, the display is updated every 1 second. Data rates will typically fall between 40-150 per second. The display may not be steady on one value, but may tend to oscillate over a range of values. Also, the data rate may drop slightly when the computer is acquiring data. This is a normal occurrence. If the data rate drops too far (<40), adjustments should be tried to increase the data rate.

B. USING THE OSCILLOSCOPE

A discussion of observing signals on the oscilloscope begins in paragraph 4.3. Although the pictures included are representative of particle bursts, they are **not** what you will see. The classical burst as shown on page 33 will only be seen for very slow moving particles. At nominal test speeds the bursts are of such short duration that the burst is compressed into nothing more than a short spike on the oscilloscope.

Noise on the signal should be kept at a minimum level by adjusting the gain. The blue signal has traditionally been noisier than the green but the cause has not yet been determined. The noise, however, has not been a problem as long as gain adjustment is monitored.

C. DATA RATE OPTIMIZING

Optimizing the data rate is subject to many variables and personal preferences. A good deal can be learned by spending time to experiment with the different switches and observing the effect on data rate and the signal on the oscilloscope.

Laser power can have a profound influence on the data rate and should be checked if data rate changes. The laser power does tend to fluctuate a little, especially when other items(i.e., wind tunnel) on the electrical circuit are turned on or off. A constant setting of laser power will mean less changes on the other controls. Power set at 2 watts has worked well.

The particle seeder should be checked if the data rate drops off during a survey with a lot of horizontal movement. This is especially true when crossing a blade surface. The dial on the nozzle control should be adjusted in small increments and the data rate observed for any changes. The distribution is usually sufficient for covering a complete blade passage without changing the setting. Observing the intensity of the laser in the flow will also give an indication of the quality of seeding.

The low limit filter should be checked if data rate drops off when moving into a region of slower moving flow. If frequency shifting is used, this should not be necessary.

The gain setting should be the primary control for adjusting the data rate after the above items are checked. The gain should not vary much from a setting of 1 on the dial. The oscilloscope must be used to monitor gain adjustments to avoid over amplifying the signal and introducing noise into the measurement.

The knob on the photomultiplier power supply is also another gain adjustment to the signal. This knob can usually be left in one position. The setting on each color may be different and has been adjusted so that a gain setting of 1 on the counter results in a good data rate. If the incoming signal is of high intensity, the warning light on the photomultiplier power supply will glow red. The gain should be reduced if the red light comes on.

The effect of noise can be observed by positioning the probe volume on a stationary object and observing the data rate as the gain is varied. The real-time histogram function of the FIND software can also be used to observe the resulting frequency distribution from noise. Note, gain settings should be lower since more light is being scattered off a stationary surface than would be scattered by the flow(avoid over amplification in the photomultiplier power supply).

VI. CASCADE WIND TUNNEL

The lab technician will help with any tunnel adjustments. Changing the tunnel to a new inlet angle will require a significant amount of reconfiguration, especially with the side walls. A full reconfiguration will take most of a day. Only those adjustments that will be necessary after the the tunnel has been reconfigured will be discussed in this section. A record book is used to record the tunnel settings for future reference.

A. INLET GUIDE VANES

The inlet guide vanes(IGV) help redirect the flow from the plenum chamber to the tunnel test section. The 59 guide vanes are connected together in two interlacing sets. The one inch spacing of the blades is designed for high mixing so that the blade wakes will mix-out before the test section. IGV adjustment must be made with the tunnel off to avoid blade flutter.

The IGVs are adjusted as a set via a screw arrangement located at the east end of the tunnel. Two rulers, one on each side of the tunnel, are used to indicate the position of the blades. The rulers are graduated in millimeters. The screw mechanism has some backlash and does not always move both guide vane sets equally. A simple method of adjusting the tunnel is to adjust the screw until the south side reads the desired value, then using a C-clamp, clamp the south blade set to a fixed support. When the south set is clamped, readjust the screw to bring the north blade set to read the same value set for the south set and clamp this set. The C-clamps are necessary to avoid drifting of the blades during tunnel operation.

B. UPPER SIDE WALLS

The purpose of the upper side walls is to direct the exit flow and to equalize the test section exit static pressure to atmospheric pressure. The upper side walls are clamped to the front and back walls and can be adjusted while the tunnel is running. The walls should be set by observing the manometer bank and adjusting the walls until the exit static pressure is uniform across the test section and equal to atmospheric pressure.

C. CHECKING THE FLOW

The manometer bank will give a good indication of how uniform the tunnel is set. Both the inlet and exit static pressures should be as uniform as possible. Since the IGV and wall settings will both affect all parts of the flow, there is no one way to set the tunnel. Consequently, the best process is to use the log book and find a setting which is close to the new setting and make an educated guess at the amount of change needed. Use the manometer board to make minor adjustments if necessary.

After the preliminary settings are made, conduct an upstream survey of the flow using the LDV system. Since the optical window does not allow a survey more than about 30% chord upstream, there will be some streamline curvature due to the test section blades. The results of the survey can then be compared to the desired inlet beta angle. Adjustments to the IGV setting should then be made and another survey conducted. If major changes to the IGVs is required, the exit side walls should also be adjusted. Repeat the adjustment process until the tunnel has a uniform pressure distribution, the desired beta inlet angle, and a uniform velocity profile.

D. ALIGNING TEMPLATE

The aligning template is used to define a fixed reference point for the LDV system relative to the trailing edge center of radius of blade seven. The aligning template is located inside a black wooden box with a Plexiglas top stored on the work table[30]. A diagram of the template is shown in Figure A-2.

The template can be installed on the blades by either climbing on top of the tunnel and reaching down into the test section, or by removing the optical window and installing the template from the front. The latter method is recommended because the access is easier and an opportunity is also afforded to clean the blade surfaces of oil accumulation.

The optical window is removed by removing a series of socket head bolts around the perimeter of the window. The window can then be pulled out and placed on the work table for cleaning. Alcohol and dry wipes works well to remove the oil.

The template is placed resting on blades 7 and 8 approximately mid-span. A small ruler can be used to measure the distance from the front edge of the blade to the template.

With the template in place, the laser is turned on and positioned using the hand controller to align with the center pinhole of the trailing edge set(labeled B in Figure A-2). When the adjustment is correct, the four beams will project on the back wall of the tunnel through the pinhole with equal intensity and no diffraction. Low power on the laser should be used because the pattern is observable without the

safety goggles. When the adjustments are set, the Sony encoder is then set to read:

X = -1.5 inches

Y = 5.0 inches

Z = 0.0 inches.

Note: The coordinate systems for the traverse table and the tunnel are not the same. Refer to Section VII, Coordinate Systems, for a description.

The template is removed and the window replaced before operating the tunnel. The Sony encoder should never be turned off to avoid losing the position from memory. It is recommended that the table always be positioned to a defined origin at the end of a survey in the event the encoder loses power. In this way, the rest position is always known and a power failure will not cause the need to repeat the alignment procedure.

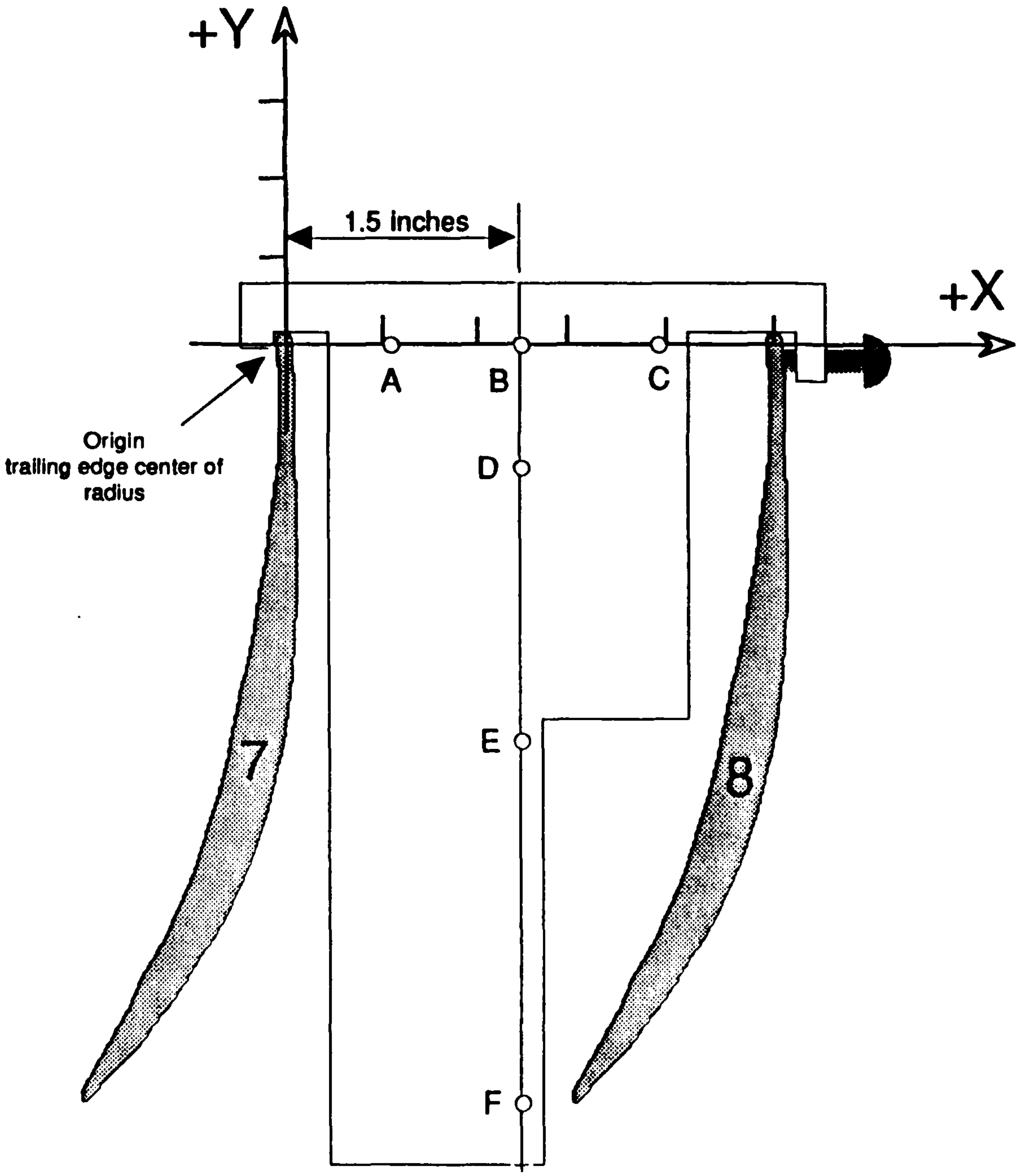

Figure A-2. LDV Blade Alignment Template

VII. COORDINATE SYSTEMS

The coordinate system used to describe locations in the cascade test section is shown in Figure A-3(a). The system is a right-hand orthogonal system with the origin at the trailing edge center of radius of blade seven. Units are in inches, with the Y direction measured vertically and the X direction measured horizontally.

Limitations on the LDV traverse table and FIND software prevent using the same coordinate system as shown in Figure A-3(a). Consequently, another coordinate system was defined as shown in Figure A-3(b). The X' axis was chosen as the horizontal to correspond as close as possible with the original system. Unfortunately, the positive direction is reversed since the software is fixed into a specific direction. Also note, the Z' axis is now equivalent to the original Y axis. For programming the traverse movements the system shown in Figure A-3(b) must be used. The software program REDRAW will automatically convert the coordinates from traverse system to the cascade system.

Velocity information will always be expressed using the cascade coordinates. Positive vertical velocity is up(measured by the green counter) and positive horizontal velocity is to the right (measured by the blue counter) as shown in Figure A-3(a). Remember, negative velocities can be measured only when frequency shifting is used.

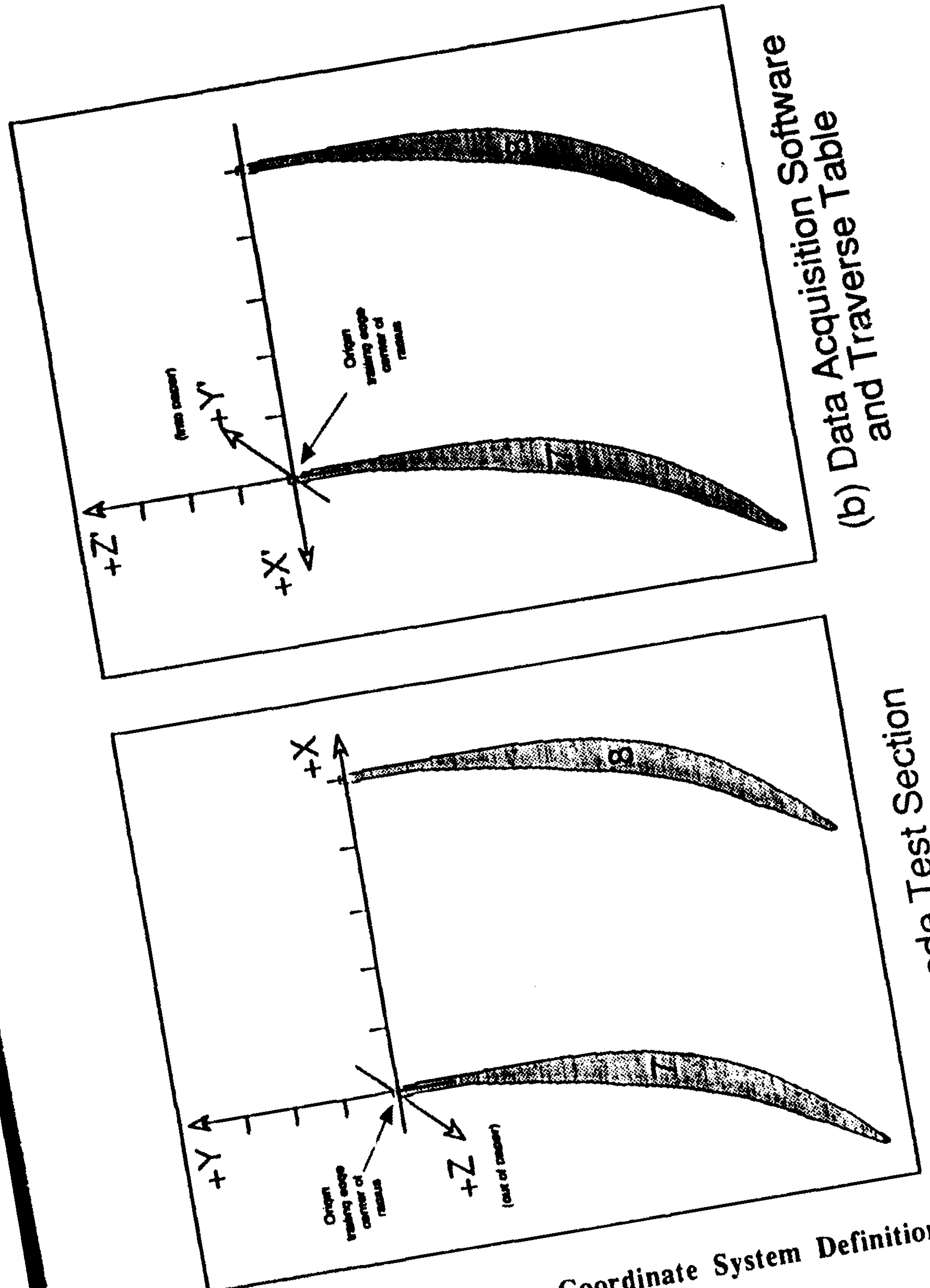

Figure A-3. Coordinate System Definitions

VIII. GENERAL TROUBLESHOOTING

If a problem develops with a piece of equipment or software refer to the appropriate manual and attempt to localize the cause of the problem. All of the manuals include sufficient guidance to solve most problems. The following discussion addresses problems which have occurred during operation and the resulting solution if any was found.

A. LASER

If a power drop occurs in the laser check the alignment of the mirrors. Adjustments are easy to perform as described in the manual.

The Etalon lens was removed because the maximum power was less than 1 watt. Previous use had caused the special coating to fog and cleaning the lens did not change the quality of the lens. Since LDV does not require the tight control of the longitudinal mode, the etalon was removed with minimal effect on the signal. If the laser is to be used for other applications(holography, interferometry) the lens should be replaced and reinstalled.

Control of the transverse mode is important. The laser plasma tube was replaced in 1986 because the tube had become defective and the primary mode had changed from TEM_{00} (gaussian) to TEM_{01} (donut). Attempts at higher power settings may induce the switch to donut mode and extremely high power settings should be avoided(this was noted particularly with the blue color by observation of the projected beam pattern).

B. COUNTERS

Overheating has been a problem with the green counter when the ambient temperature is high (above 75 °F). The problem manifests itself as a loss of data rate on the readout module while the counter and timer appear to be functioning properly as indicated by the lights and oscilloscope signal. The only solution is to cool the counter or wait until the temperature is cooler. Do not continue to operate if this condition occurs because damage may occur. The counter has been serviced twice for this overheat problem but the servicing has obviously not solved the problem. The blue counter has not exhibited this problem.

Module swapping between the two counters can be used to isolate a problem, however, care must be taken when removing the modules from the cabinets as the pins on the back of the modules have a tendency to push the sockets out of connector resulting in a faulty connection. This was noted particularly with the Input Conditioner Module of the green counter. The resulting error manifested as a misrepresentation of the number of cycles being sent to the computer as monitored by the Hardware Diagnostic selection of the Data Acquisition Program. The result will be extremely high velocities being calculated. This problem can be fixed by removing the module and reaching behind the connector inside the cabinet to push the sockets back into the connector. Then, carefully insert the module back into the cabinet and check for proper data transfer. A signal generator can be used for trouble shooting. Of course, this problem can be avoided altogether by leaving the modules in the cabinet.

C. AUTOMATED TRAVERSE TABLE

Reference:

TSI Incorporated, *Model 9500 Traverse Table System Instruction Manual,* 1987

At the time this manual was written the traverse was not properly working with the FIND software. Extensive troubleshooting to find the cause of the problem resulted in no solution. Traversing in the X direction is working properly but the Y and Z direction both do not interface correctly. Consequently, the cabling has been changed on the control box and the Sony encoder so that the X direction is the horizontal movement, making horizontal surveys easier to accomplish. If the problem is ever resolved the cabling could be changed back but the software routines that have been generated will need to be modified to reflect the coordinate system change. In any case, the coordinate systems between the table, FIND software and the tunnel do not match and therefore, changing the cables will not serve any purpose.

When entering a position to move the traverse table from the FIND software, the Y and Z directions will be interpreted as a relative movement rather than an absolute position. After the first move is made the computer will check to see how close it is and then will properly interpret the position as an absolute position. The resulting movement is to the desired position but via an indirect route. However, if the desired position is near zero (less than the resolution limit), the table will not move that axis at all. The X axis works properly and does not require modification in use.

To move to zero in the Y and Z direction, a work around solution is to enter a small number near zero which is just larger than the resolution limit. Additionally, for horizontal type surveys (wake, inlet, passage), entering zero for the Y and Z axes will result in no change or attempted movement in those directions.

IX. POINTS OF CONTACT

LASER

Lexel Corporation	Service Department: Vincent Wong{ x 3005}
928 East Meadow Drive	NOTE: This company was being sold and may
Palo Alto, CA 94303	not be at this location or phone number.
(415) 770-0800	

LASER OPTICS / TRAVERSE TABLE / SOFTWARE

TSI Incorporated	Local Salesman: Alton Purvis {(408) 452-0808}
500 Cardigan Road	Hardware: Jagadish Buddhavarapu
St. Paul, MN 55164	Rajan Menon
(612) 483-0900	Software: Stephen Schlosser
1- (800) 234-8822	Service: Jerry Haider

APPENDIX B- COMPUTER PROGRAM LISTINGS

REDRAW.BAS

This program was written in Microsoft Quick Basic running on the IBM PC/AT. The program reads raw data files output from TSI FIND software and converts the data to velocity, turbulence and position information. The output is in a form readable by LOTUS 1-2-3.

```
100 CLS
110 PRINT : PRINT
114 PRINT "THIS PROGRAM WILL REDUCE RAW DATA FILES GENERATED BY THE"
115 PRINT "TSI FIND PROGRAM (LDV DATA ACQUISITION AND STATISTICS PROGRAM)."
116 PRINT "FILES MUST BE FROM A 2 COUNTER/COINCINDENCE MODE DATA SET."
117 INPUT "DO YOU WISH TO CONTINUE (Y/N) "; ANS$
118 IF (LEFT$(ANS$, 1) = "N" OR LEFT$(ANS$, 1) = "n") THEN GOTO 5000
119 PRINT : PRINT : PRINT
120 INPUT "ENTER DRIVE\DIRECTORY SPECIFICATION(C:\LDVDATA): ", DRIVE$
130 INPUT "ENTER RAW DATA FILE FAMILY NAME (NO EXTENSION): ", FILENM$
140 FILESPEC$ = DRIVE$ + "\" + FILENM$ + ".R"
150 PRINT : PRINT
160 ON ERROR GOTO 500
170 FILES FILESPEC$ + "*"
180 INPUT "ENTER FIRST FILE AND LAST FILE, SEPARATE BY COMMA(0,0 to STOP): ", STRT%, FIN%
190 IF (STRT% OR FIN%) = 0 THEN GOTO 5000
200 PRINT : PRINT
210 PRINT "FILE SPEC IS "; FILESPEC$; "  FOR "; STRT%; " TO "; FIN%
220 INPUT " IS THIS CORRECT (Y/N) "; ANS$
230 IF (LEFT$(ANS$, 1) = "N" OR LEFT$(ANS$, 1) = "n") THEN GOTO 110
```

```
231 INPUT "DO YOU WANT TO REFINE THE DATA (Y/N) "; ANS$
232 IF (LEFT$(ANS$, 1) = "Y" OR LEFT$(ANS$, 1) = "y") THEN GOTO 236
234 REFINE = 10
235 GOTO 240
236 INPUT "ENTER NUMBER OF STANDARD DEVIATIONS FOR REFINMENT "; REFINE
240 PRINT : PRINT : PRINT "PREPARING TO READ THE FILE HEADERS"
250 DIM DRP(FIN%, 10): DIM BUF$(58)
260 FOR I = STRT% TO FIN%
270 IF (I < 10) THEN EXT$ = "0" + RIGHT$(STR$(I), 1) ELSE EXT$ =
    RIGHT$(STR$(I), 2)
280 FILE$ = FILESPEC$ + EXT$
290 PRINT : PRINT "OPENING FILE: "; FILE$
300 OPEN FILE$ FOR INPUT AS #1
310 FOR J = 1 TO 58
320 BUF$(J) = INPUT$(22, #1)
330 NEXT 'J
340 DRP(I, 1) = VAL(BUF$(10))'#K DATA POINTS
350 DRP(I, 2) = VAL(BUF$(24))'FRINGE SPACING COUNTER 0
360 DRP(I, 3) = VAL(BUF$(25))'FRINGE SPACING COUNTER 1
370 DRP(I, 4) = VAL(BUF$(28))'FREQUENCY SHIFTING COUNTER 0 IN MHz
380 DRP(I, 5) = VAL(BUF$(29))'FREQUENCY SHIFTING COUNTER 1 IN MHz
390 DRP(I, 6) = VAL(BUF$(56))'X POSITION IN INCHES
400 DRP(I, 7) = VAL(BUF$(57))'Y POSITION IN INCHES
410 DRP(I, 8) = VAL(BUF$(58))'Z POSITION IN INCHES
412 DRP(I, 9) = VAL(BUF$(7))' NUMBER OF COUNTERS
415 DRP(I, 10) = VAL(BUF$(6))' CHECK FOR COINCIDENCE MODE (CO=0)
420 IF (DRP(I, 9) = 2 AND DRP(I, 10) = 0) THEN 430
425 IF (DRP(I, 9) = 1) THEN PRINT "CANNOT PROCESS SINGLE COUNTER DATA
    FILES."
426 GOTO 428
427 PRINT "CANNOT PROCESS DATA TAKEN IN A RANDOM MODE."
428 CLOSE #1
429 GOTO 110
430 CLOSE #1
```

```
440 NEXT 'I
450 ERASE BUF$
460 GOTO 1000
500 IF (ERR = 53 OR ERR = 64) THEN GOTO 520
510 GOTO 540
520 INPUT "COULD NOT FIND THE FILE. DO YOU WANT TO TRY AGAIN ", ANS$
525 IF (LEFT$(ANS$, 1) = "N" OR LEFT$(ANS$, 1) = "n") THEN GOTO 5000
530 GOTO 110
540 PRINT "UNEXPECTED ERROR ERROR NUMBER ", ERR, "ERROR LINE ", ERL
550 GOTO 5000
1000 OUTPUT$ = DRIVE$ + "\" + FILENM$ + ".DAT"
1001 OUTSORT$ = DRIVE$ + "\" + FILENM$ + ".SRT"
1010 PRINT : PRINT "OPENING OUTPUT FILE. RESULTS WILL BE APPENDED. ";
     OUTPUT$
1020 OPEN OUTPUT$ FOR APPEND AS #2
1030 FOR I = STRT% TO FIN%
1040 IF (I < 10) THEN EXT$ = "0" + RIGHT$(STR$(I), 1) ELSE EXT$ =
     RIGHT$(STR$(I), 2)
1050 FILE$ = FILESPEC$ + EXT$
1060 PRINT : PRINT "OPENING RAW DATA FILE FOR DATA: "; FILE$
1070 OPEN FILE$ FOR RANDOM AS #1 LEN = 10
1080 RECD% = DRP(I, 1) * 1024
1090 FIELD #1, 2 AS A1$, 2 AS B1$, 2 AS A0$, 2 AS B0$, 2 AS TBD$
1100 DIM BUF(RECD%, 2)
1110 SUMU = 0!: SUMU2 = 0!: SUMV = 0!: SUMV2 = 0!
1120 STDEVU = 0!: STDEVV = 0!: TURBU = 0!: TURBV = 0!
1130 PRINT : PRINT "TRANSFORMING DATA INTO VELOCITY INFORMATION."
1140 PRINT "ALSO MAKING FIRST PASS ON STATISTICS. STANDBY."
1150 FOR J = 1 TO RECD%
1160 GET #1, J + 336 'OFFSET 336 RECORDS(FILE HEADER 3360 BYTES)
1162 NMFRG1 = (CVI(A1$) AND 255!) 'FILTER OUT ADDRESS OF THE PROCESSOR
1164 NMFRG0 = (CVI(A0$) AND 255!)
1170 MAN1 = (CVI(B1$) AND 4095)
1180 MAN0 = (CVI(B0$) AND 4095)
```

```
1190 'MANTBD=(CVI(TBD$) AND 4095)
1200 EXP1 = 0
1210 IF (CVI(B1$) AND 4096) = 4096 THEN EXP1 = EXP1 + 1
1220 IF (CVI(B1$) AND 8192) = 8192 THEN EXP1 = EXP1 + 2
1230 IF (CVI(B1$) AND 16384) = 16384 THEN EXP1 = EXP1 + 4
1240 EXP0 = 0
1250 IF (CVI(B0$) AND 4096) = 4096 THEN EXP0 = EXP1 + 1
1260 IF (CVI(B0$) AND 8192) = 8192 THEN EXP0 = EXP1 + 2
1270 IF (CVI(B0$) AND 16384) = 16384 THEN EXP0 = EXP1 + 4
1280 'EXPTBD=0
1290 'IF (CVI(TBD$) AND 4096)=4096 THEN EXPTBD=EXPTBD+1
1300 'IF (CVI(TBD$) AND 8192)=8192 THEN EXPTBD=EXPTBD+2
1310 'IF (CVI(TBD$) AND 16384)=16384 THEN EXPTBD=EXPTBD+4
1320 BURST1 = MAN1 * 2 ^ (EXP1 - 3)
1330 BURST0 = MAN0 * 2 ^ (EXP0 - 3)
1340 'TBD = MANTBD*2^(EXPTBD-3)
1350 BUF(J, 1) = DRP(I, 2) * (NMFRG0 * 1000! / BURST0 - DRP(I, 4))
1360 BUF(J, 2) = DRP(I, 3) * (NMFRG1 * 1000! / BURST1 - DRP(I, 5))
1370 U = BUF(J, 1)
1380 V = BUF(J, 2)
1390 SUMU = SUMU + U
1400 SUMU2 = SUMU2 + U * U
1410 SUMV = SUMV + V
1420 SUMV2 = SUMV2 + V * V
1430 NEXT 'J
1440 CLOSE #1
1450 GOSUB 2000
1460 WRITE #2, I, (-1) * DRP(I, 6), DRP(I, 7), DRP(I, 8), MEANU, MEANV,
      TURBU, TURBV, RECD%, ACCEPT%
1470 ERASE BUF
1480 NEXT I
1485 PRINT : PRINT "CLOSING OUTPUT FILE."
1490 CLOSE #2
1495 ERASE DRP
```

```
1500 PRINT : INPUT "WOULD YOU LIKE TO PROCESS MORE DATA (Y/N) "; ANS$
1510 IF (LEFT$(ANS$, 1) = "N" OR LEFT$(ANS$, 1) = "n") THEN GOTO 5000
1511 PRINT : INPUT "Use the same directory and family name(Y/N) ", ANS$
1512 IF (LEFT$(ANS$, 1) = "N" OR LEFT$(ANS$, 1) = "n") THEN GOTO 110
1513 GOTO 170
1520 END
2000 REM SUBROUTINE FOR STATISTIC CALC
2010 MEANU = SUMU / RECD%
2020 MEANV = SUMV / RECD%
2030 STDEVU = SQR((SUMU2 - SUMU * SUMU / RECD%) / (RECD% - 1))
2040 STDEVV = SQR((SUMV2 - SUMV * SUMV / RECD%) / (RECD% - 1))
2050 TURBU = STDEVU / MEANU
2060 TURBV = STDEVV / MEANV
2065 PRINT "COUNTER", "    MEAN", "  TURB(%)", "  STDEV"
2070 PRINT "  1  ", MEANU, TURBU * 100, STDEVU
2075 PRINT "  2  ", MEANV, TURBV * 100, STDEVV
2080 PRINT : PRINT "FIRST PASS COMPLETE. REFINING STATISTICS."
2090 REM  NOW REFINE THE STATISTICS
2110 LOWU = MEANU - STDEVU * REFINE
2120 HIGHU = MEANU + STDEVU * REFINE
2130 LOWV = MEANV - STDEVV * REFINE
2140 HIGHV = MEANV + STDEVV * REFINE
2150 SUMU = 0!: SUMU2 = 0!: SUMV = 0!: SUMV2 = 0!
2160 STDEVU = 0!: STDEVV = 0!: TURBU = 0!: TURBV = 0!
2170 ACCEPT% = 0
2180 FOR K = 1 TO RECD%
2190 U = BUF(K, 1)
2200 V = BUF(K, 2)
2210 IF (U < LOWU) OR (U > HIGHU) THEN 2280
2220 IF (V < LOWV) OR (V > HIGHV) THEN 2280
2230 ACCEPT% = ACCEPT% + 1
2240 SUMU = SUMU + U
2250 SUMU2 = SUMU2 + U * U
2260 SUMV = SUMV + V
```

```
2270 SUMV2 = SUMV2 + V * V
2280 NEXT 'K
2290 MEANU = SUMU / ACCEPT%
2300 MEANV = SUMV / ACCEPT%
2310 STDEVU = SQR((SUMU2 - SUMU * SUMU / ACCEPT%) / (ACCEPT% - 1))
2320 STDEVV = SQR((SUMV2 - SUMV * SUMV / ACCEPT%) / (ACCEPT% - 1))
2330 TURBU = STDEVU / MEANU
2340 TURBV = STDEVV / MEANV
2345 PRINT "COUNTER", "    MEAN", "   TURB(%)", "   STDEV"
2350 PRINT "   1   ", MEANU, TURBU * 100, STDEVU
2355 PRINT "   2   ", MEANV, TURBV * 100, STDEVV
2360 PRINT : PRINT "REFINDED STATISTICS COMPLETE."
2380 RETURN
5000 'chains back to menu page
5010 CHAIN "c:\find\auxmenu.EXE"
5020 END
```

AUXMENU.BAS

This program was written in Microsoft Quick Basic running on the IBM PC/AT. The program acts as an auxiliary menu to link the FIND software and the REDRAW program.

```
10 DEFINT A-Z
20 Q = 2
30 WHILE Q >= 1
40 CLS : PRINT : PRINT : PRINT : PRINT : PRINT :
50 PRINT TAB(35); "Main Menus": PRINT : PRINT : PRINT
60 COLOR 15, 0: PRINT TAB(30); "   D"; : COLOR 7, 0: PRINT "ata
     Reduction(RAW to Stats)"
70 COLOR 15, 0: PRINT TAB(30); "   Q"; : COLOR 7, 0: PRINT "uit"
80 PRINT : PRINT TAB(30); "Select: ";
90 Q$ = INPUT$(1): Q = INSTR("DQdq", Q$) ' Get valid key
10 IF Q = 0 GOTO 75
110 CLS       ' Take action based on key
120 ON Q GOSUB 200, 500, 200, 500
130 WEND
140 ' Transfers to the  data Reduction Program
150 CHAIN "c:\find\redraw.exe"
160 RETURN
170 ' Quit
190 END
```

LDVREM.BAS

This program was written in HP Basic running on the HP 9000 computer. The program records tunnel plenum pressure and temperature by use of a remote switch accessible from the IBM terminal.

```
10   ! LDVREM  : kdm 06/07/89
20   ! Main program for collecting tunnel conditions during an LDV survey
30   ! Uses subroutines for reading scanner,scanivalve,and dvm
40   !------------------------------------------------------------------------
50   ! This program will read the cascade plenum pressure and temperature
60   ! and store the results to an ASCII file.
70   ! One set of readings will consist of :
80   !      1) read temperature (average of 5 readings)
90   !      2) read pressure (average of 3 ensembles , 5 readings each)
100  !         spread over a timespan of 25 seconds
110  !      3) read temperature again and then average with the first.
120  ! Inputs required from the user are:
130  !      1) Name of data file to store results
140  !      2) Barometric Pressure in INCHES of HG
150  ! The user should have already adjusted the zero and span of the
160  ! dvm for the scanner prior to using the program.
170  !---------------------------------------------------------------------
180  OPTION BASE 1 ! sets arrays to start at an index of 1 instead of 0
190  ! define the common block for passing the system identifiers
200  COM /Sys/ Bus,Scn,Dvm,Svm,Svc,Scv(5,5)
210  !---------------------------------------------------------------------
220  ! define the local constants
230  Pzero=1!zero pressure (guage)
240  Pplenum=3! plenum port is #2
250  Tplenum=10! plenum temperature is on scanner #10
260  Svalve=2! using scani-valve #2
270  !---------------------------------------------------------------------
280  ! define the local variables
290  ! Nameout$ = Output file name
300  ! Filenm$  = Complete path identifier
310  ! @Pathout = Filenm$
320  ! ans$     = input holder
330  ! counter  = Number of runs
340  ! Flag     = check for continue or exit the program
350  ! Psum     = holder for average count
360  ! Pout     = volts from DVM
370  ! Pzout    = zero reading from scani-valve
380  ! Fp       = pressure in H2O (delta p , avg)
390  ! Pbaro    = barometric pressure (input inches Hg, output Inches H2O)
400  ! Tsum     = holder for average count
410  ! Tout     = volts from DVM
420  ! T        = converted to deg F
430  ! Tp       = plenum temperature in deg F (avg)
440  !---------------------------------------------------------------------
```

```
450   ! run itialization of system and set scani-valves to port 1
460   LOADSUB ALL FROM "/CASCADE/Initial"
470   CALL Initial
480   DELSUB Initial
490   WAIT 3
500   ON ERROR RECOVER Errors
510   DIM Nameout$[8],Filenm$[30]
520   OUTPUT 1;CHR$(7)
530   WAIT .2
540   OUTPUT 1;CHR$(7)
550   CAT "DATA"
560   INPUT "Enter name of output file for storage of data:",Ans$
570   Nameout$[1]=UPC$(Ans$[1,8])
580   Filenm$="/CASCADE/DATA/"&Nameout$[1]
590   OUTPUT 1;"data will be stored in :";Filenm$
600   CREATE ASCII Filenm$,10
610   ASSIGN @Path_out TO Filenm$
620   GOTO 720
630   ! error checking routine for file input
640 Errors:   !
650   IF ERRN=54 THEN
660     PRINT "The file already exists. Pleas try again."
670   ELSE
680     PRINT "error is ";ERRN
690     STOP
700   END IF
710   GOTO 550
720  ! input of barometric pressure
730   INPUT "Enter barometric pressure in INCHES Hg",Pbaro
740   PRINT "Barometric Pressure is ",Pbaro
750   INPUT "Is this correct?",Ans$
760   IF UPC$(Ans$[1])="Y" THEN
770     GOTO 810
780   ELSE
790     GOTO 730
800   END IF
810   Pbaro=Pbaro*13.596 ! converts to inches of H2O
820   ! prints to file as first record #0
830   OUTPUT @Path_out;0,0,0,0,0,0,0,Pbaro,0
840   Counter=1
850   Flag=0
860   DIM Tout(2),Pout(3)
870   CLEAR SCREEN
880 Measure:CALL Rsw(40,Flag)
890   SELECT Flag
900   CASE 0
910     PRINT "Data point #";Counter
920     Psum=0
930     Tsum=0
940     Tout(1)=0
950     Tout(2)=0
```

```
960     Pout(1)=0
970     Pout(2)=0
980     Pout(3)=0
990     Pzout=0
1000        ! First temperature measurement
1010    CLEAR Scn
1020    CLEAR Dvm
1030    CALL Rdvchnl(Tplenum,5,100,Tout(1))
1040    Tout(1)=ABS(Tout(1))*1000
1050    T=32.028+(35.642)*Tout(1)-(.33539)*Tout(1)*Tout(1)
1060    Tsum=Tsum+Tout(1)
1070    PRINT "Starting Temperature is ";T;" in deg F."
1080        ! pressure measurements
1090        ! First read zero for pressure
1100    CLEAR Scn
1110    CLEAR Dvm
1120    CALL Rscv(Svalve,Pzero,5,Pzout)
1130    PRINT 0,Pzout*10^4
1140      ! now read 3 times for plenum pressure
1150    FOR I=1 TO 2
1160      CALL Rscv(Svalve,Pplenum,5,Pout(I))
1170      PRINT I,(Pout(I)-Pzout)*10^4
1180      WAIT 5! wait additional time between reads
1190    NEXT I
1200    CALL Rscv(Svalve,Pplenum,5,Pout(3))
1210    Psum=Pout(1)+Pout(2)+Pout(3)
1220    PRINT I,(Pout(3)-Pzout)*10^4
1230    Pp=((Psum/3)-Pzout)*10^4
1240    PRINT "Average pressure is ";Pp;" IN of H2O (gauge)"
1250    CLEAR Scn
1260    CLEAR Dvm
1270    CALL Rdvchnl(Tplenum,5,100,Tout(2))
1280    Tout(2)=ABS(Tout(2))*1000
1290    T=32.028+35.642*Tout(2)-.33539*Tout(2)*Tout(2)
1300    Tsum=Tsum+Tout(2)
1310    PRINT "Final temperature is ";T;" in deg F."
1320    T=Tsum/2
1330    Tp=32.028+35.642*T-.33539*T*T
1340    PRINT "Average temperature is ";Tp;" in deg F."
1350        ! send raw and converted values of Pzero,Pp and Tp to file
1360    OUTPUT @Path_out;Counter,Pzout,Pout(1),Pout(2),Pout(3),Tout(1),Tout(2),P
p;Pbaro,Tp+460
1370    Counter=Counter+1
1380    OUTPUT 1;CHR$(7)
1390    GOTO Measure
1400  CASE 1
1410  ! done with measurements
1420      ! Resets scani-valve to port 1
1430    CLEAR Scn
1440    CLEAR Dvm
1450    CALL Rscv(Svalve,1,1,Pout(1))
1460    CLEAR Scn
1470    CLEAR Dvm
1480  END SELECT
1490  END
```

```
1500  SUB Rscv(Scvno,Port,Rno,Value)! kdm 05/25/89
1510  ! modified from Moyle routines
1520  ! routine positions and reads scanivalve on dvm
1530  !-------------------------------------------------------------------
1540    OPTION BASE 1
1550    COM /Sys/ Bus,Scn,Dvm,Svm,Svc,Scv(5,5)
1560    INTEGER Iscvno,Bport
1570    Iscvno=Scvno
1580    Portreqd=Port*Scv(Scvno,5)
1590  !.....start positioning
1600 Read:OUTPUT Svc USING "#,K";Iscvno  !select valve in controller
1610    Bport=SPOLL(Svc)
1620    U=BINAND(Bport,15)
1630    V=SHIFT(Bport,4)
1640    T=BINAND(V,7)
1650    Portnow=10*T+U
1660    CLEAR Svc
1670 Chck:IF Portnow=Portreqd THEN Goon
1680 Test:IF Portreqd>Portnow THEN
1690      OUTPUT Scn USING "ZZ";Scv(Scvno,3)         !step scv
1700      CLEAR Scn
1710      WAIT .5
1720      GOTO Read
1730    ELSE
1740      OUTPUT Scn USING "ZZ";Scv(Scvno,4)         !home scv
1750      CLEAR Scn
1760      WAIT 4.0          !wait for scv to reset to (01)
1770      GOTO Read
1780    END IF
1790 Goon:          !scv on port reqd/ update Scv
1800    Scv(Scvno,1)=Portnow/Scv(Scvno,5)
1810    WAIT .5           !wait .5 sec for stabilization of pressure
1820!read dvm for data value
1830    CALL Rdvchnl(Scv(Scvno,2),Rno,100,Value)
1840  SUBEND
1850  SUB Rdvchnl(Chnl,Rno,Rdy,Value) ! kdm 05/25/89
1860  ! Modified from Moyle
1870  ! routine reads dvm Rno times at intervals of Rdy
1880  !-----------------------------------------------------------------
1890    OPTION BASE 1
1900    COM /Sys/ Bus,Scn,Dvm,Svm,Svc,Scv(5,5)
1910    OUTPUT Scn USING "ZZ";INT(Chnl)
1920    WAIT .1!wait for relay to make
1930    OUTPUT Dvm;"F1R7T2T3A0D0"
1940    Vsum=0
1950    FOR I=1 TO Rno
1960      WAIT Rdv/1000
1970      TRIGGER Dvm
1980      ENTER Dvm;V0
1990      DISP "Rdv",Chnl,I,V0
2000      Vsum=Vsum+V0
2010    NEXT I
2020    Value=Vsum/Rno
2030  SUBEND
```

```
2040  SUB Rsw(Minutes,Ok)! kdm 05/28/89
2050  !Modified from MOYLE "Rsw"
2060  !routine times out on remote switch at compressor after Minutes
2070  !looks for low resistance(short) to continue
2080  !----------------------------------------------------------------
2090    OPTION BASE 1
2100  ! Local Constants and variables
2110  ! 58 = Light address on scanner
2120  ! 14 = Remote switch address on scanner
2130  ! Ok = flag if done with measurements:
2140  !      = 0 : continue taking data
2150  !      = 1 : stop taking data (EXIT) Pressed
2160  ! Ohms = output from DVM
2170  !----------------------------------------------------------------
2180    COM /Sys/ Bus,Scn,Dvm,Svm,Svc,Sc.(5,5)
2190    ON KEY 1 LABEL "EXIT" GOTO Finish
2200    ON KEY 2 LABEL "CONT" GOTO Go_on
2210    ON KEY 3 LABEL "" GOTO Loop
2220    ON KEY 4 LABEL "" GOTO Loop
2230    KEY LABELS ON
2240  ! get time stamp from operating system
2250    T0=TIMEDATE
2260    Ok=0
2270    OUTPUT Scn USING "ZZ";58!set light on
2280    OUTPUT Scn USING "ZZ";14!set scn to remote sw chnl
2290    OUTPUT Dvm;"F4R5T2A0H0D0"!set dvm to read resistance
2300    DISP "Waiting for REMOTE SWITCH CLOSE / or press CONT (f2) or EXIT (f1)"
2310 Loop:TRIGGER Dvm
2320       ! read DVM for resistance
2330    ENTER Dvm;Ohms
2340    IF Ohms<1000 THEN     ! shorted (switch is closed)
2350      GOTO Go_on
2360    ELSE
2370      WAIT .5
2380    END IF
2390    IF TIMEDATE-T0<Minutes*60 THEN Loop
2400    IF TIMEDATE-T0>Minutes*60 THEN Leave
2410 Go_on:CLEAR Scn !set light off
2420    KEY LABELS OFF
2430 Leave:SUBEXIT
2440 Finish:Ok=1 ! sets flag to 1 for EXIT condition
2450    SUBEXIT
2460  SUBEND
```

```
10    SUB Initial
20    !Initial- kdm 05/25/89
30    !Modified from Moyle 'ACQ-CONNFIG'
40    !program defines contents of common area Sys
50    !area is reserved for bus and unit identification AND scanivalve
60    !control (advancing,reading,reset etc.) data
70    !=================================================================
80    OPTION BASE 1
90    COM /Sys/ Bus,Scn,Dvm,Svm,Svc,Scv(5,5)
100   !.......acq units
110   Bus=7
120   Scn=709
130   Dvm=722
140   Svm=724
150   Svc=707
160   !.......svc control channels on scanner
170   DISP "SET ALL SCANIVALVE CHANNELS TO (01)/ PRESS CONT (f2) WHEN DONE"
180   PAUSE
190   FOR I=1 TO 5
200   Scv(I,1)=1!current port
210   Scv(I,2)=I-1!data channel on scn
220   Scv(I,3)=39+I!port advance channel on scanner
230   Scv(I,4)=44+I!valve reset channel on scanner
240   Scv(I,5)=1!step increment/ set to (2) for 24 port scv
250   NEXT I
251   DISP "INITIALIZATION OF COMMON BLOCK VARIABLES IS COMPLETE."
260   SUBEND
```

PRINTDAT.BAS

This program was written in HP Basic running on the HP 9000 computer. The program prints the tunnel plenum pressure and temperature recorded by LDVREM.

```
10    OPTION BASE 1
20    CLEAR SCREEN
21    DIM Filenm$[22]
30    PRINT "This Program will output to the screen and printer"
40    PRINT "the results for Cascade plenum pressure and temperature."
50    CAT "/CASCADE/DATA"
60    PRINT
70    PRINT
80    PRINT
90    PRINT "RUN#","PRESSURE","TEMPERATURE"
100   PRINT "","  IN H2O","   DEG R"
110   OUTPUT 1;CHR$(7);
120   WAIT .4
130   OUTPUT 1;CHR$(7)
140   INPUT "Enter File name to read from.",Name$
150   Name$[1]=Name$[1,8]
160   Filenm$="/CASCADE/DATA/"&Name$
170   ASSIGN @Datfile TO Filenm$
180   ASSIGN @Printer TO 701
190   ON END @Datfile RECOVER 450
200   !OUTPUT @Printer;CHR$(12)
210   OUTPUT @Printer;"File Name: ";Filenm$
220   OUTPUT @Printer;""
230   OUTPUT @Printer;""
240   OUTPUT @Printer;"  RUN#";"    PRESSURE";"   TEMPERATURE"
250   OUTPUT @Printer;"      ";"     IN H2O ";"      DEG R"
260   OUTPUT @Printer;""
270   Counter=6
280   REPEAT
290     ENTER @Datfile;K,Pzero,Pout(1),Pout(2),Pout(3),Tout(1),Tout(2),Pp,Tp
300     PRINT USING Fmt1;K,Pp,Tp
310     OUTPUT @Printer USING Fmt1;K,Pp,Tp
320     Counter=Counter+1
330     IF Counter=55 THEN
340       OUTPUT @Printer;CHR$(12)
350       OUTPUT @Printer;"File Name: ";Filenm$
360       OUTPUT @Printer;""
370       OUTPUT @Printer;""
380       OUTPUT @Printer;"  RUN#";"    PRESSURE";"   TEMPERATURE"
390       OUTPUT @Printer;"      ";"     IN H2O ";"      DEG F"
400       OUTPUT @Printer;""
410       Counter=6
420     END IF
```

```
430 Fmt1:IMAGE 4D,8D.DDD,8D.DDD
440   UNTIL ERRN=59
450   PRINT "File is out of data. Done."
460   OUTPUT @Printer;CHR$(12)
470   END
```

APPENDIX C- SYSTEM EQUATIONS

A. VELOCITY NORMALIZATION

The method used for velocity normalization was covered in Elazar's dissertation [Ref. 9] and is repeated in this section. A relationship will be developed which expresses a reference upstream velocity in terms of the tunnel plenum pressure and temperature.

The plenum chamber pressure and temperature are measured. Assuming velocity in the plenum chamber to be very low,

$M_p << 1$

$p_p \cong P_p$ and $T_p \cong T_t$.

Since flow in the tunnel is subsonic, $M \cong 0.25$, density is assumed to be constant. Losses across the lower part of the tunnel and the inlet guide vanes are represented as a loss in pressure by the total pressure loss coefficient

$$\varpi_g = \frac{P_p - P_{t1}}{q_p}$$

Solving for P_{t1},

$$P_{t1} = P_p - \varpi_g q_p$$

Dynamic pressure from the plenum is then expressed in terms of the inlet dynamic pressure and inlet flow angle as

$$q_p = q_1 \cos^2 \beta_1$$

Substituting,

$$P_{t1} = P_p - \varpi_g q_1 \cos^2 \beta_1 \tag{1}$$

Losses across the test section are represented in a similar fashion

$$\varpi_b = \frac{P_{t1} - P_{t2}}{q_1}$$

and, therefore

$$P_{t1} = P_{t2} + \varpi_b q_1 = p_2 + q_1 \frac{\cos^2 \beta_1}{\cos^2 \beta_2} + \varpi_b q_1 = p_1 + q_1$$

giving

$$p_1 = p_2 + q_1 \left(\frac{\cos^2 \beta_1}{\cos^2 \beta_2} + \varpi_b - 1 \right) \tag{2}$$

Assuming isentropic, perfect gas flow, it is possible to express the relationship between upstream stagnation and static pressure in terms of a non-dimensional velocity, X_V, by the equation

$$\frac{P_{t1} - p_1}{P_{t1}} = 1 - \frac{p_1}{P_{t1}} = \nu(X_v) \tag{3}$$

where

$$X_v = \frac{V}{\sqrt{2C_p T_{t1}}} \tag{4}$$

and

$$\nu(X_v) = \frac{\gamma}{\gamma - 1}(X_v)^2 \left(1 - (X_v)^2\right)^{\frac{1}{\gamma - 1}} \tag{5}$$

Combining Equations 1, 2, and 3

$$1 - \frac{p_2 + q_1\left(\dfrac{\cos^2 \beta_1}{\cos^2 \beta_2} + \varpi_b - 1\right)}{P_p - \varpi_g q_1 \cos^2 \beta_1} = \nu(X_v) \tag{6}$$

Then, under the assumptions that:

1) exit static pressure, p_2, is approximately atmospheric pressure, p_{atm}
2) $\varpi_g < 0.1$, and $\varpi_b < 0.1$
3) velocities in the test section are less than 100 m/s, ($X_v \leq 0.1$)

Equation 6 becomes

$$1 - \frac{p_2}{P_p} \cong \frac{P_p - p_{atm}}{p_{atm}} = C_{p12}\nu(X_v) \tag{7}$$

where C_{p12}, the reference velocity normalizing loss coefficient, is a constant for small variations in X_v.

The reference velocity normalizing loss coefficient, C_{p12}, is experimentally determined for a given tunnel configuration by conducting an inlet reference survey upstream of the test blade using the LDV system to measure the velocity at nominal test speeds. From velocity and plenum temperature, the non-dimensional velocity can be obtained using Equation 4. With X_v now known, using the plenum pressure, atmospheric pressure, and Equations 5 and 7, the reference velocity normalizing loss coefficient, C_{p12}, can be obtained.

The reference inlet velocity, V_{ref}, for subsequent measurements is obtained using Equation 7, rewritten as

$$\nu(X_v) = \frac{P_p - p_{atm}}{p_{atm}}\left(\frac{1}{C_{p12}}\right)$$

Equation 5 is then solved iteratively for X_v. Finally, from Equation 4, V_{ref} is given by

$$V_{ref} = X_v\sqrt{2C_pT_{t1}}$$

B. LDV REDUCTION

The principle equations used in the LDV reduction process are summarized as follows:

Fringe spacing

$$d_f = \frac{\lambda}{2\sin\kappa}$$

Doppler Frequency/Velocity Relation

$$\left|f_D \pm f_{shift}\right| = \frac{2u_i \sin\kappa}{\lambda_i} = \frac{u_i}{d_f}$$

Measuring Volume

define:

$$d_{e^{-2}} = \frac{4\lambda f}{\pi D_{e^{-2}}}$$

Note: The diameter D_{e-2} is based on the light incident to the main lens referenced to a gaussian beam distribution before beam expansion of 1mm (i.e. D_{e-2}=3.75x1mm).

Measuring volume length

$$l_m = \frac{d_{e^{-2}}}{\sin \kappa}$$

Measuring volume diameter

$$d_m = \frac{d_{e^{-2}}}{\cos \kappa}$$

number of fringes in measuring volume

$$N_{FR} = \frac{d_m}{d_f}$$

C. DATA REDUCTION

Velocities measured by the two counters are corrected for yaw angle and roll, allowing for different optical configurations, using the following equations:

roll angle = ϕ

yaw angle = γ

$$u = \left(\frac{u_m \cos(\phi) - v_m \sin(\phi)}{\cos(\gamma)} \right)$$

$$v = u_m \sin(\phi) + v_m \cos(\phi)$$

$$V_{loc} = \sqrt{u^2 + v^2}$$

Local turbulence intensity is defined as

$$\varepsilon_{loc} = \frac{\sqrt{\dfrac{\left(\frac{\varepsilon_{um}}{100} u_m\right)^2 + \left(\frac{\varepsilon_{vm}}{100} v_m\right)^2}{2}}}{V_{loc}} \times 100 \,(\text{in } \%)$$

Turbulence intensity referenced to inlet conditions

$$\varepsilon = \frac{\varepsilon_{loc}}{V_{ref}} V_{loc}$$

where V_{ref} is defined as described previously in Section A of this appendix.

REFERENCES

1. NASA Special Publication SP-36, *Aerodynamic Design of Axial Flow Compressors*, edited by Irving A. Johnson and Robert A. Bullock, 1965.

2. Sanger, N. L., "The Use of Optimization Techniques to Design Controlled Diffusion Compressor Blading," *ASME Journal of Engineering for Power*, v. 105, pp.256-264, April 1983.

3. Himes, S. J., *Report of Tests of a Compressor Configuration of DCA Blading*, Master's Thesis, Naval Postgraduate School, Monterey, California, June 1983.

4. Koyuncu, Y., *Report of Tests of a Compressor Configuration of CD Blading*, Master's Thesis, Naval Postgraduate School, Monterey, California, March 1984.

5. Sanger, N. L., and Shreeve, R. P., "Comparison of Calculated and Experimental Cascade Performance for Controlled Diffusion Compressor Stator Blading," *ASME Journal of Turbomachinery*, v. 108, pp.42-50, April 1986.

6. Deutsch, S., and Zierke, W. C., "The Measurement of Boundary Layers on a Compressor Blade in Cascade: Part 1– A Unique Experimental Facility," *ASME Journal of Turbomachinery*, v. 109, pp.520-526, October 1987.

7. Deutsch, S., and Zierke, W. C., "The Measurement of Boundary Layers on a Compressor Blade in Cascade: Part 2– Suction Surface Boundary Layers," *ASME Journal of Turbomachinery*, v. 110, pp.138-145, January 1988.

8. Deutsch, S., and Zierke, W. C., "The Measurement of Boundary Layers on a Compressor Blade in Cascade: Part 3– Pressure Surface Boundary Layers and the Near Wake," *ASME Journal of Turbomachinery*, v. 110, pp.146-152, January 1988.

9. Elazar, Y., *A Mapping of the Viscous Flow Behavior in a Controlled Diffusion Compressor Cascade Using Laser Doppler Velocimetry and Preliminary Evaluation of Codes for the Prediction of Stall*, Ph.D. Dissertation, Naval Postgraduate School, Monterey, California, March 1988.

10. Elazar, Y. and Shreeve, R. P., "Viscous Flow in a Controlled Diffusion Compressor Cascade with Increasing Incidence," AMSE paper 89-GT-131 presented at the Gas Turbine and Aeroengine Congress and Exposition, Toronto, Canada, June 4-8, 1989.

11. Deutsch, S., and Zierke, W. C., "The Measurement of Boundary Layers on a Compressor Blade in Cascade: Part 4– Flow Fields for Incidence Angles of -1.5 and 8.5 Degrees," AMSE paper 89-GT-72 presented at the Gas Turbine and Aeroengine Congress and Exposition, Toronto, Canada, June 4-8, 1989.

12. Holman, J. P., *Experimental Methods for Engineers*, 4th ed., pp. 59-73, McGraw-Hill Book Company, 1984.

BIBLIOGRAPHY

NASA Contractor Report 177386, *Laser Doppler Velocimetry Primer*, by W. D. Bachalo, December 1985.

NASA Contractor Report 177390, *A 3-Component Laser-Doppler Velocimeter Data Acquisition and Reduction System*, by L. C. Rodman, J. H. Bell, and R. D. Mehta, January 1986.

Putman, B. W.,*RS-232 Simplified*, Prentic-Hall, Inc., 1987.

INITIAL DISTRIBUTION LIST

1.	Defense Technical Information Center Cameron Station Alexandria, Virginia 22304-6145	2
2.	Library, Code 0142 Naval Postgraduate School Monterey, California 93943-5002	2
3.	Naval Air Systems Command Washington, D.C. 20361 Attention: Code AIR 931E	1
4.	Naval Air Systems Command Washington, D.C. 20361 Attention: Code AIR 5004	4
5.	Office of Naval Research 800 N. Quincy Street Arlington, Virginia 22217 Attention: J. Hansen, Code 113	1
6.	Naval Air Propulsion Center Trenton, New Jersey 08628 Attention: G. Mangano, PE-31	1
7.	National Aeronautics & Space Administration Lewis Research Center 21000 Brookpark Center Cleveland, Ohio 44135 Attention: N. Sanger (MS: 5-11)	1
8.	Chairman, Code 67 Department of Aeronautics and Astronautics Naval Postgraduate School Monterey, California 93943	1
9.	Professor R. P. Shreeve, Code 67Sf Department of Aeronautics and Astronautics Naval Postgraduate School Monterey, California 93943	10

10. Professor S. K. Hebbar, Code 57Hb
Department of Aeronautics and Astronautics
Naval Postgraduate School
Monterey, California 93943

1

11. LT Kenneth D. Murray
1892 Carmelita Dr.
San Carlos, California 94070

2